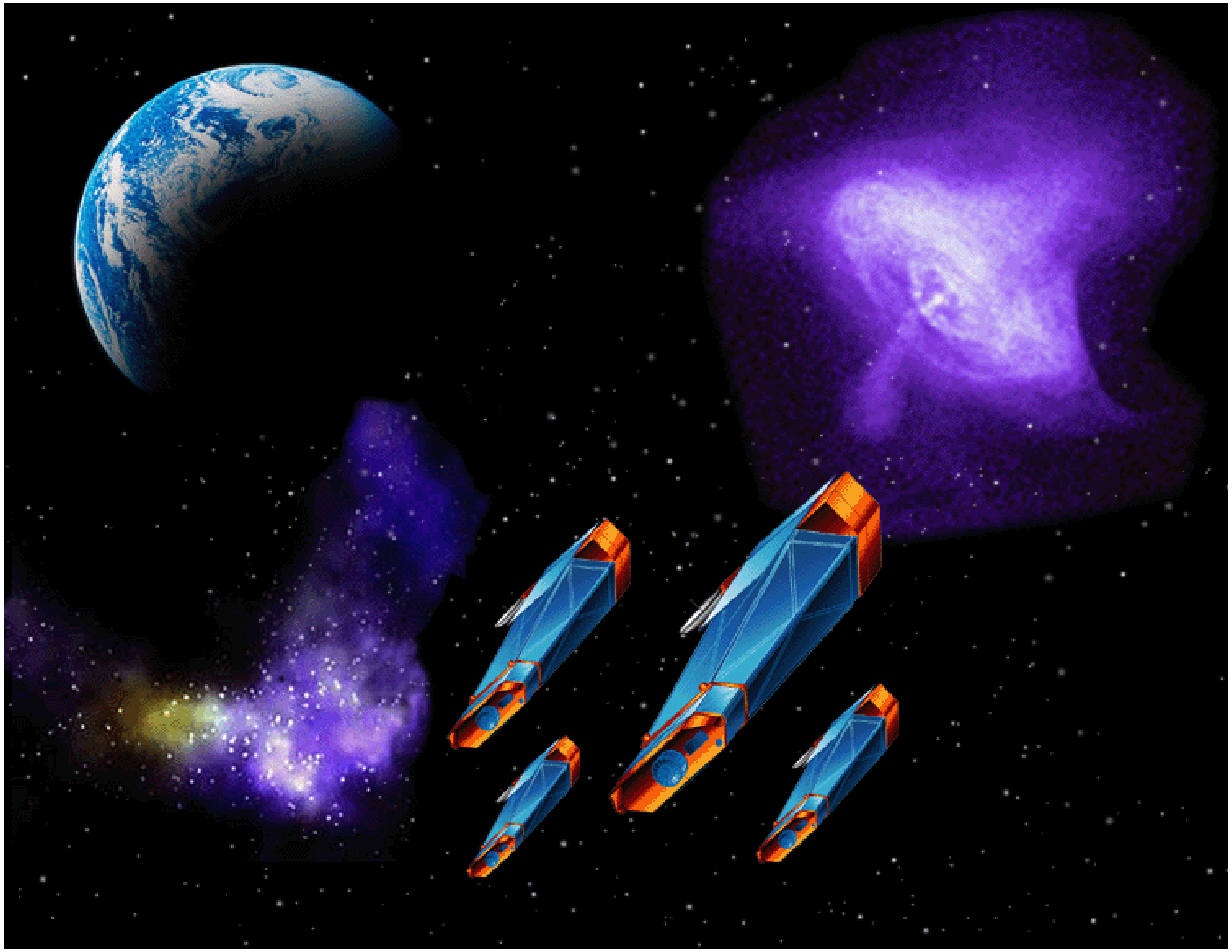
# Constellation X-ray Mission



**http://constellation.gsfc.nasa.gov**

# Constellation-X Mission Overview


An X-ray VLT

## Use X-ray spectroscopy to observe

- Black holes: strong gravity & evolution
- Dark Matter throughout the Universe
- Production and recycling of the elements

## Mission parameters

– **Telescope area:** 3 $m^2$ at 1 keV
*25-100 times XMM/Chandra for high resolution spectroscopy*

– **Spectral resolving power:** 300-3,000
*5 times better than Astro-E2 at 6 keV*

– **Band pass:** 0.25 to 40 keV
*100 times RXTE sensitivity at 40 keV*

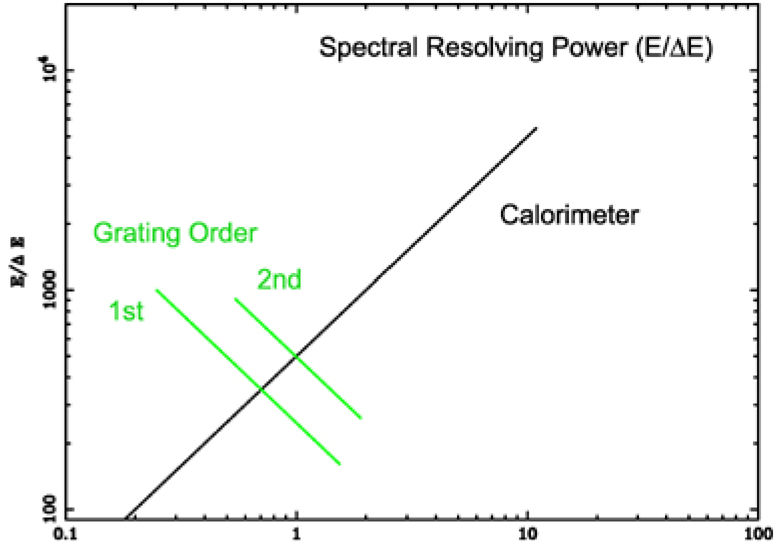
**Enable high resolution spectroscopy of faint X-ray source populations**

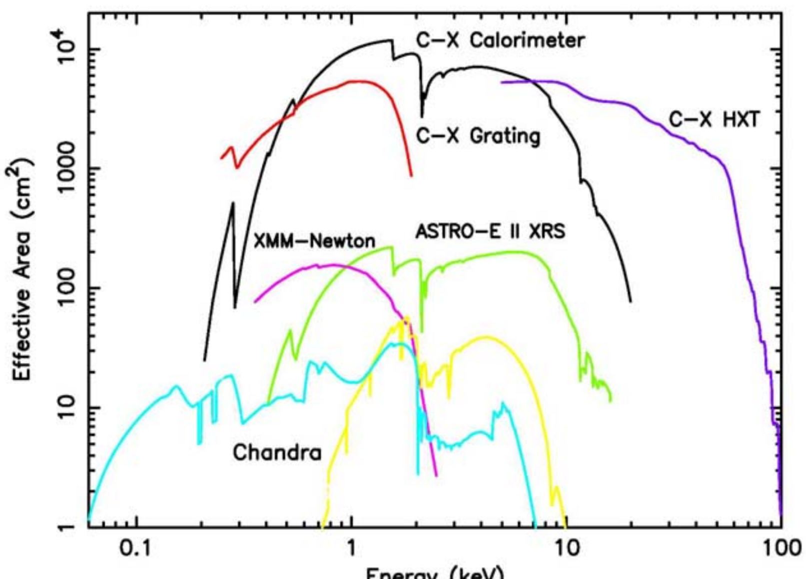
# McKee-Taylor Survey Highlights Constellation-X

- The Constellation-X mission received strong endorsement from the National Academy of Sciences McKee-Taylor Astronomy and Astrophysics survey committee of new facilities for the 2000-2010 timeframe
  - Constellation-X ranked 2nd in large space based mission category after the Next Generation Space Telescope, ahead of the Terrestrial Planet Finder
- From the report:
  - “Constellation-X Observatory is the premier instrument to probe the formation and evolution of black holes... the first clusters of galaxies... quasars at high redshift... and the formation of the chemical elements…”
  - “Constellation-X will complement Chandra, much as Keck and Gemini complement HST…”
  - “it has been under study for 5 years and the technology issues are well in hand for a start in the middle of the decade”

# Constellation-X Mission Performance

## Two coaligned telescope systems cover the 0.25 to 40 keV band




**SXT: Spectroscopy X-ray Telescope**

- 0.25 to 10 keV
- Effective area:
  - ➔15,000 sq cm at 1 keV
  - ➔ 6,000 sq cm at 6 keV
- Resolution 300-3000 with combination of
  - ➔ 2eV microcalorimeter array
  - ➔ reflection grating/CCD
- 5-15 arc sec HPD angular resolution
  - ➔ 5 arc sec pixels, 2.5 arc min FOV

**HXT: Hard X-ray Telescope**

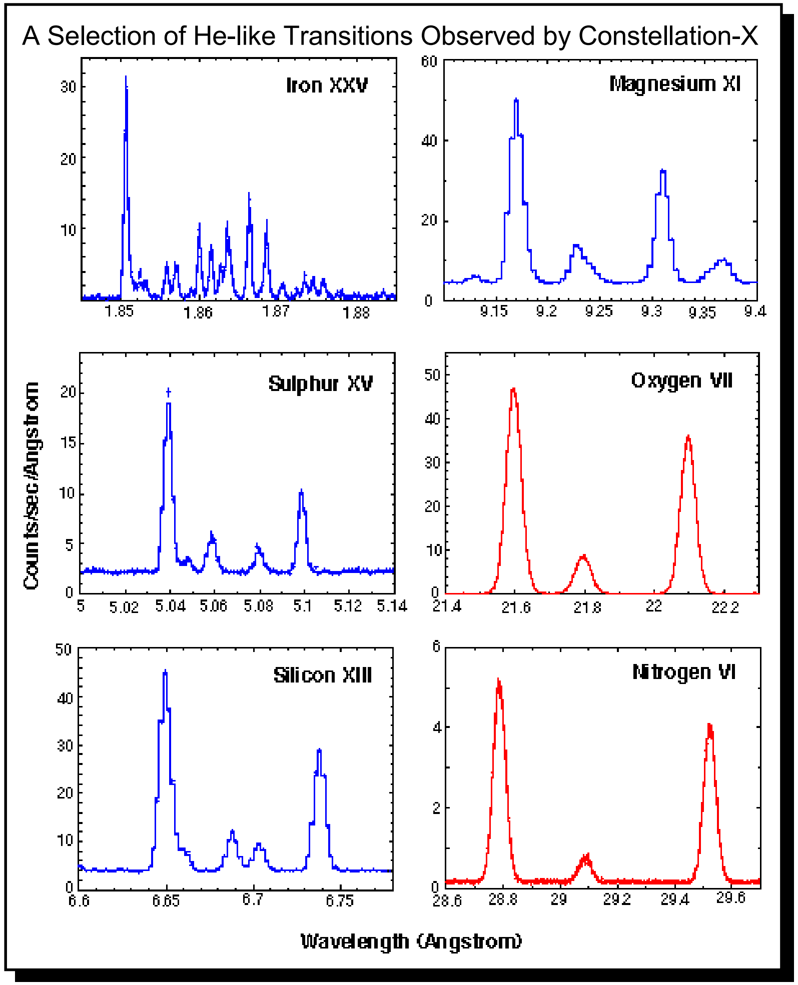
- 10 to 60 keV
  - ➔1,500 sq cm at 40 keV
- Energy resolution < 1 keV
- 30-60 arc sec HPD angular resolution

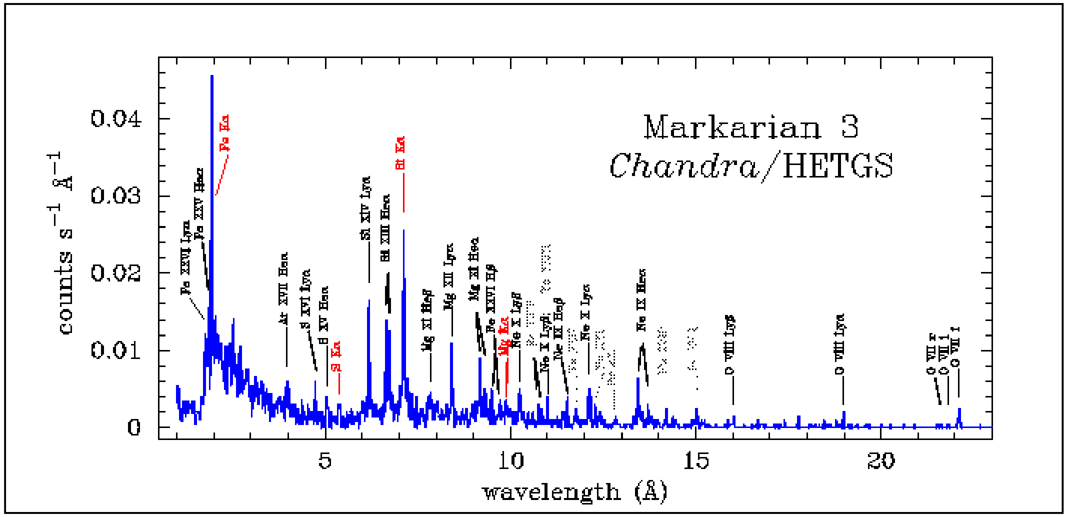
**Overall factor of 20-100 increased sensitivity**

- gives ~ 1000 counts in $10^5$ s for a flux of 2 x $10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ (0.1 to 2.0 keV)

# Plasma Diagnostics with Constellation-X

The Constellation-X energy band contains the K-line transitions of 25 elements allowing simultaneous direct abundance determinations using line-to-continuum ratios

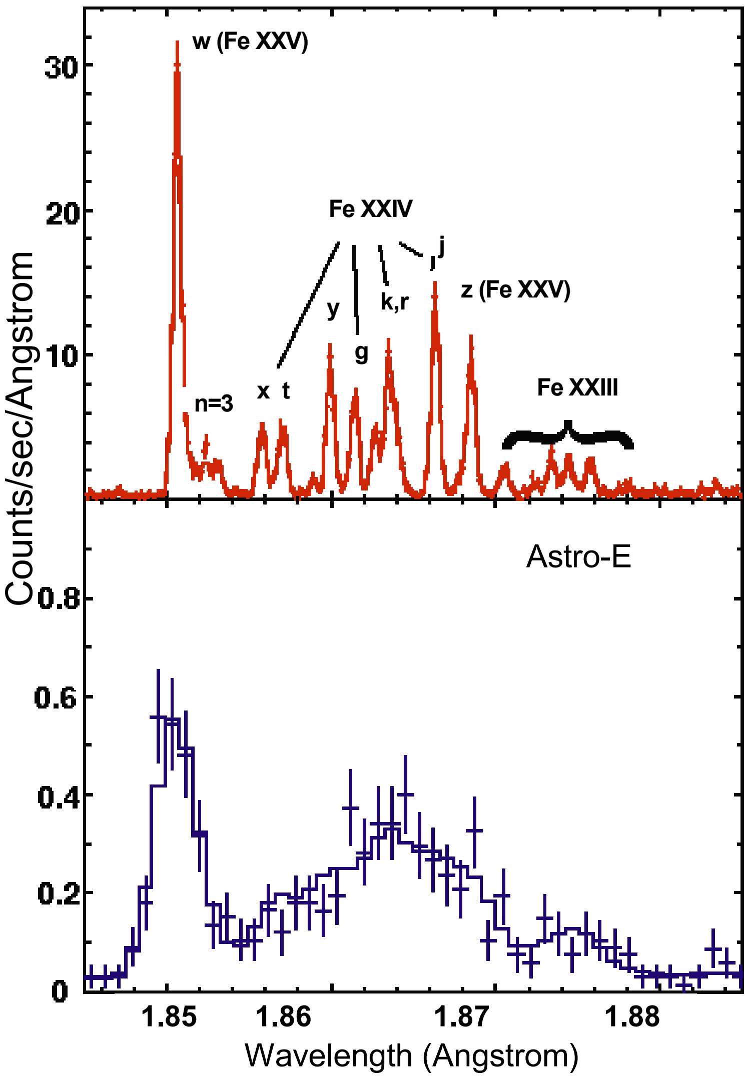



The spectral resolution of Constellation-X is tuned to study the He-like density sensitive transitions of Carbon through Zinc

# Constellation-X Micro-calorimeter Array

Simulated 80,000 s AR Lac Observation of Fe XXV

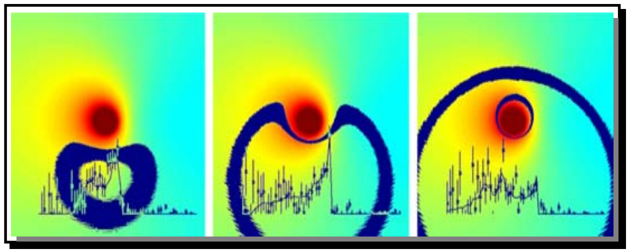



High quantum efficiency with the capability to map extended sources

- **A factor of 5 improvement (2 eV) in spectral resolution with R ~ 3000-4000 in iron K band (compared to ~10 eV for Astro-E2)**
- **At Iron K, 2 eV resolution gives a bulk velocity of 100 km/s & line energy centroiding capability equivalent to an absolute velocity of 10 km/s**
- **≥ 2.5 × 2.5 arc min field of view with 30 x 30 pixels (vs 6 x 6 for XRS)**
- **Ability to handle 1,000 ct/sec/pixel**

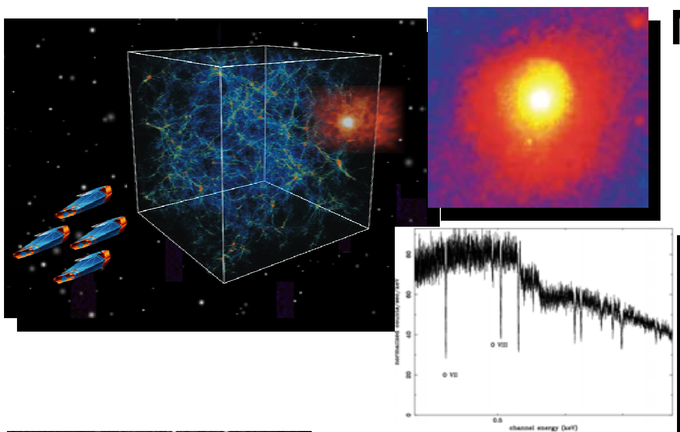
# Science Highlights

***Constellation-X is an observatory class mission that brings high resolution X-ray spectroscopy into the mainstream of astronomy***



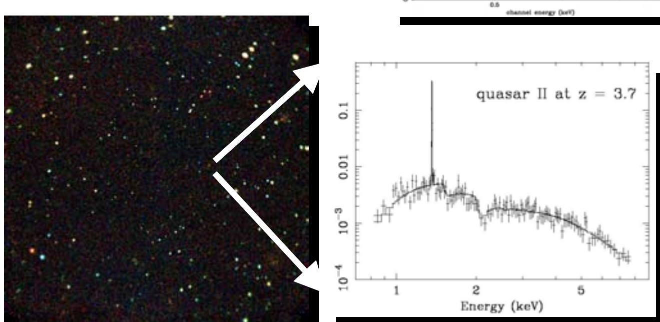
**Observe the effects of General Relativity near black hole event horizons**

- Probe 100,000 times closer to black hole event horizon than at longer wavelengths
- Determine black hole spin and mass from iron profiles over a wide range of luminosity and redshift



**Map formation and evolution of dark matter structures throughout the Universe**

- Detect ionized gas in the hot Inter Galactic Medium via absorption lines in spectra of background quasars
- Map the distribution of dark and baryonic matter trapped in the gravitational potential of clusters of galaxies
- Observe the faintest, most distant clusters of galaxies to constrain Cosmological models and parameters

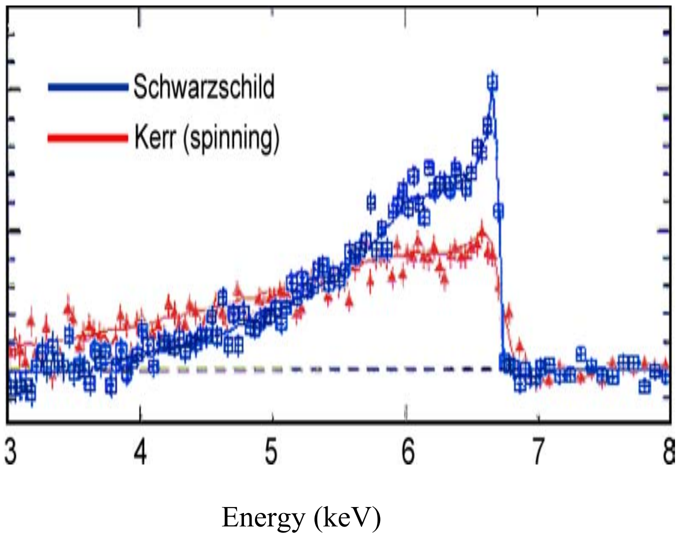



Chandra Deep Field

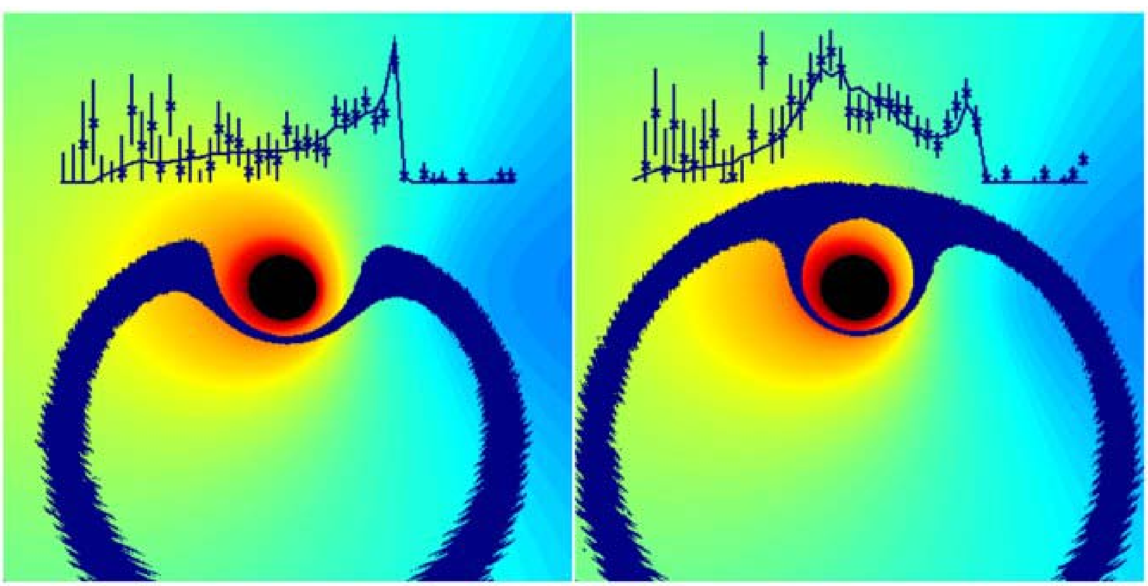
**Determine the nature of the faint X-ray sources discovered by Chandra**

- Obtain detailed spectra to determine physical processes prevalent in redshifts ranging out to ~5 or more
- AGN, Starburst galaxies

# Black Holes and Strong Gravity

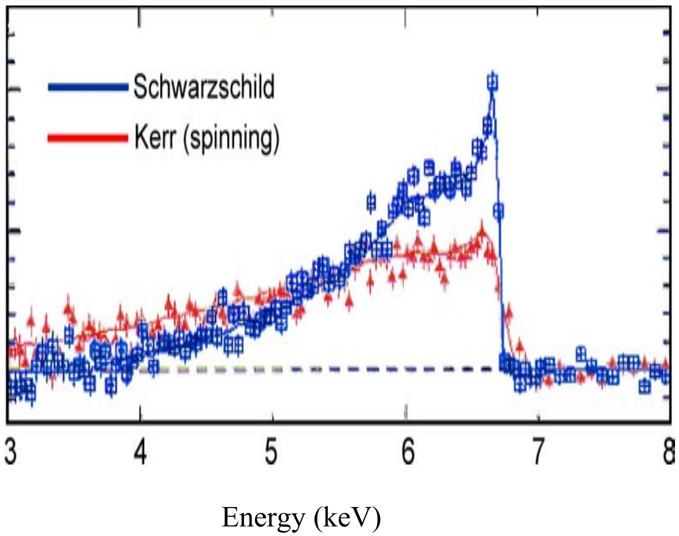



- **Constellation-X will probe close to the event horizon with 100 times better sensitivity than before**
  - **Observe iron profile from close to the event horizon where strong gravity effects of General Relativity are seen**
  - **Investigate evolution of black hole properties by determining spin and mass over a wide range of luminosity and redshift**



***Simulated images of the region close to the event horizon illustrate the wavefront of a flare erupting above material spiralling into the black hole. The two spectra (1000 seconds apart) show substantial distortions due to GR effects.***

# Black Holes and Strong Gravity

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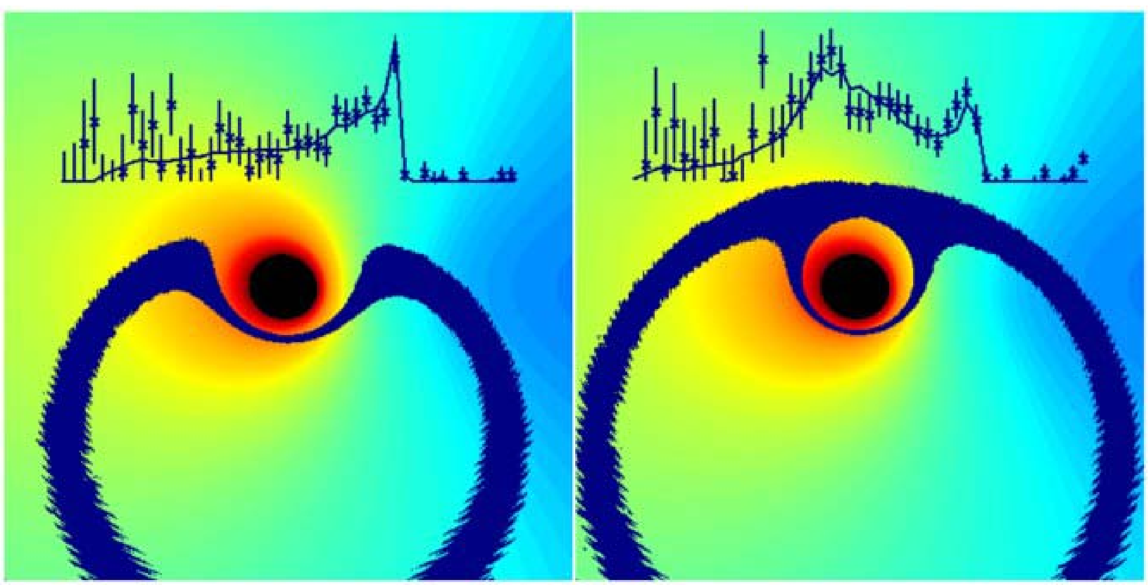
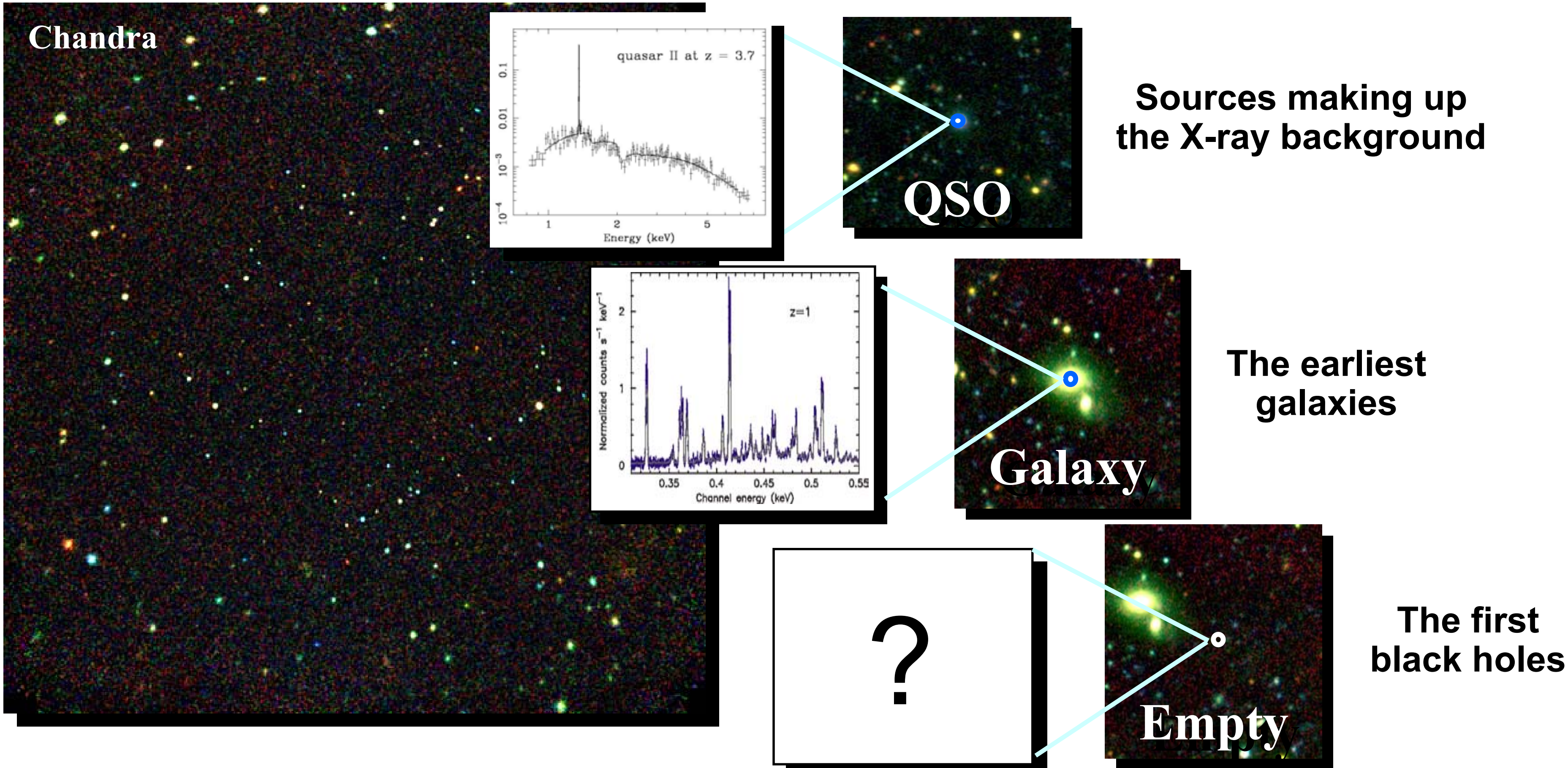


***Simulated images of the region close to the event horizon illustrate the wavefront of a flare erupting above material spiralling into the black hole. The spectra show substantial distortions due to GR effects.***

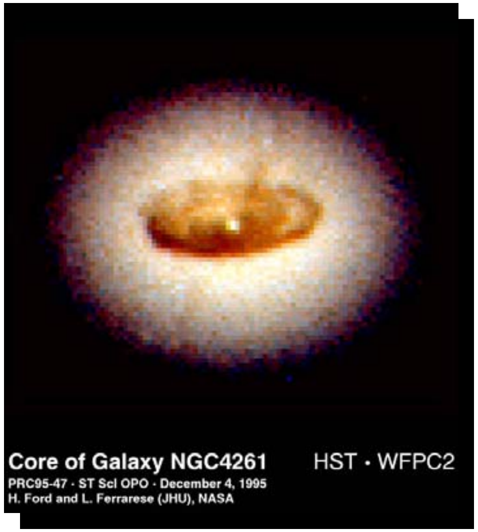
# Black Hole Evolution

***Chandra deep field has revealed what may be some of the most distant objects ever observed***

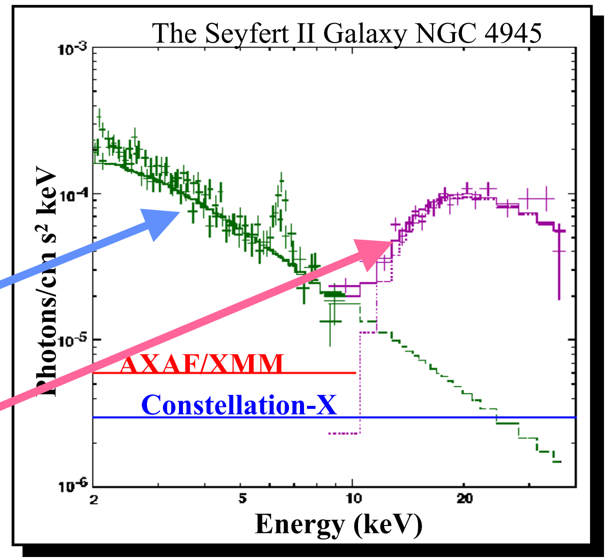



**Constellation-X will obtain high resolution spectra of these faintest X-ray sources to determine redshift and source conditions**

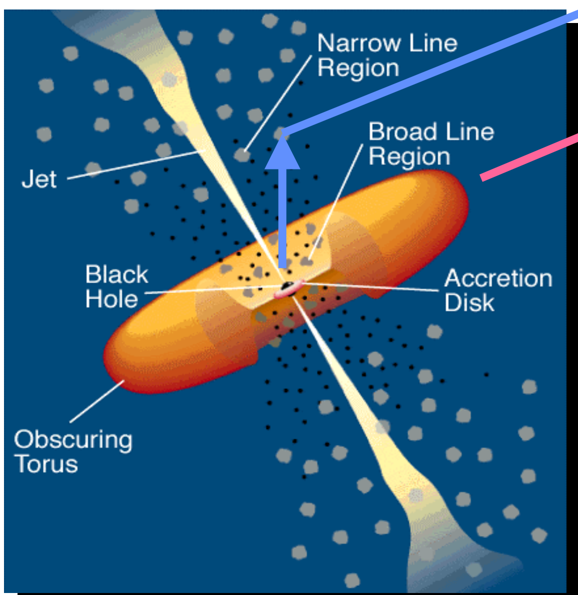
# Hidden Black Holes




***Many black holes may be hidden behind an inner torus or thick disk of material***

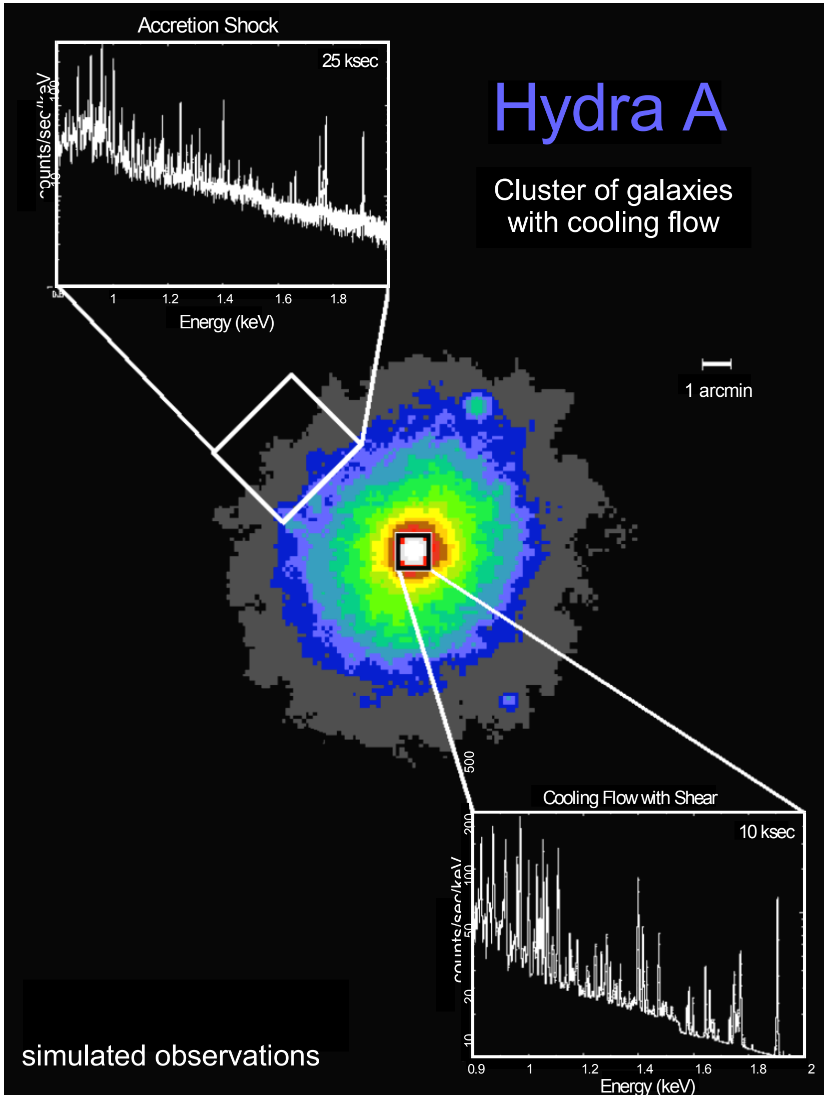



**Only visible above 10 keV where current missions have poor sensitivity**




**Constellation-X will use multi-layer coatings on focusing optics to increase sensitivity at 40 keV by >100 over Rossi XTE**

# When Were Clusters of Galaxies Formed and How Do They Evolve?



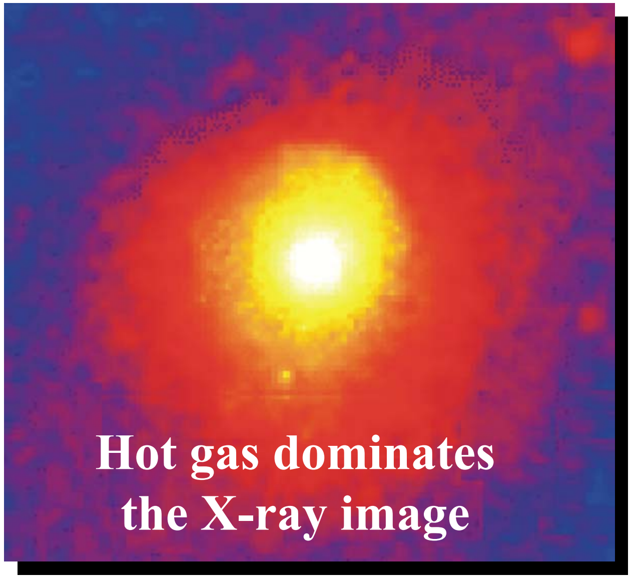

**Clusters of galaxies provide a uniquely useful probe of Cosmology**

- Clusters are “simple” objects that are fair samples of the universe - they reflect the underlying dark matter to baryon ratio
- The abundance and redshift distribution of clusters determine the geometry of the universe
- Merging clusters can be used to test dark matter models
- Cluster elemental abundance measurements provide a powerful “dust free” measure of the star formation history of the Universe

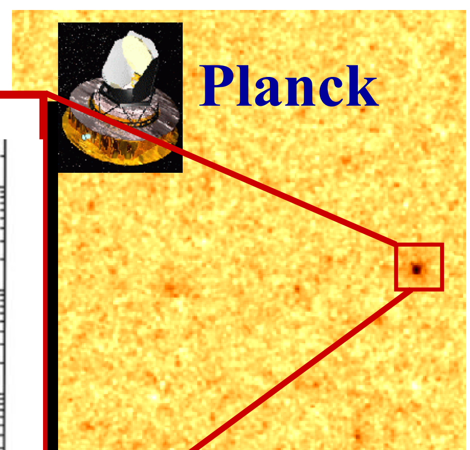
**Constellation-X observations of clusters of galaxies are essential to understand structure, evolution, and mass content of the Universe**

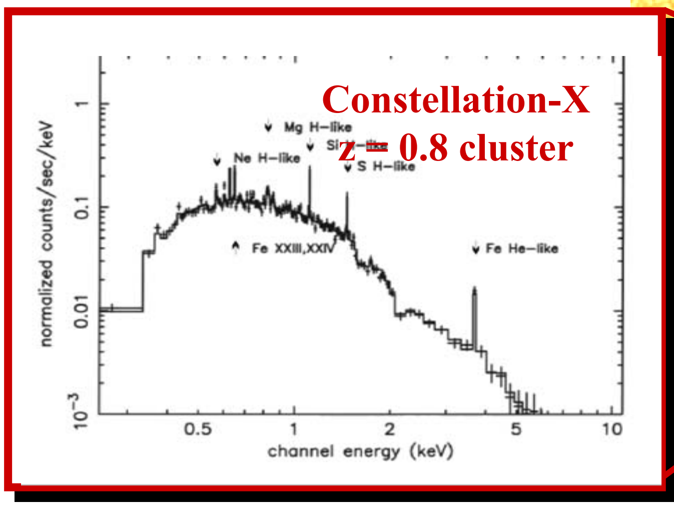
# Cosmology with Clusters of Galaxies

Galaxies seen in the optical image



Hot gas dominates the X-ray image




Microwave background and X-ray surveys will find clusters at all redshifts

Precision spectroscopy by Constellation-X of faintest, most distant clusters will determine redshift and cluster mass and the evolution of their parameters with redshift

# The Missing Hydrogen Mystery

**An inventory of the visible matter in today's Universe gives only 20% of the baryons (mostly Hydrogen) found at high redshift in the Lyman-alpha forest**

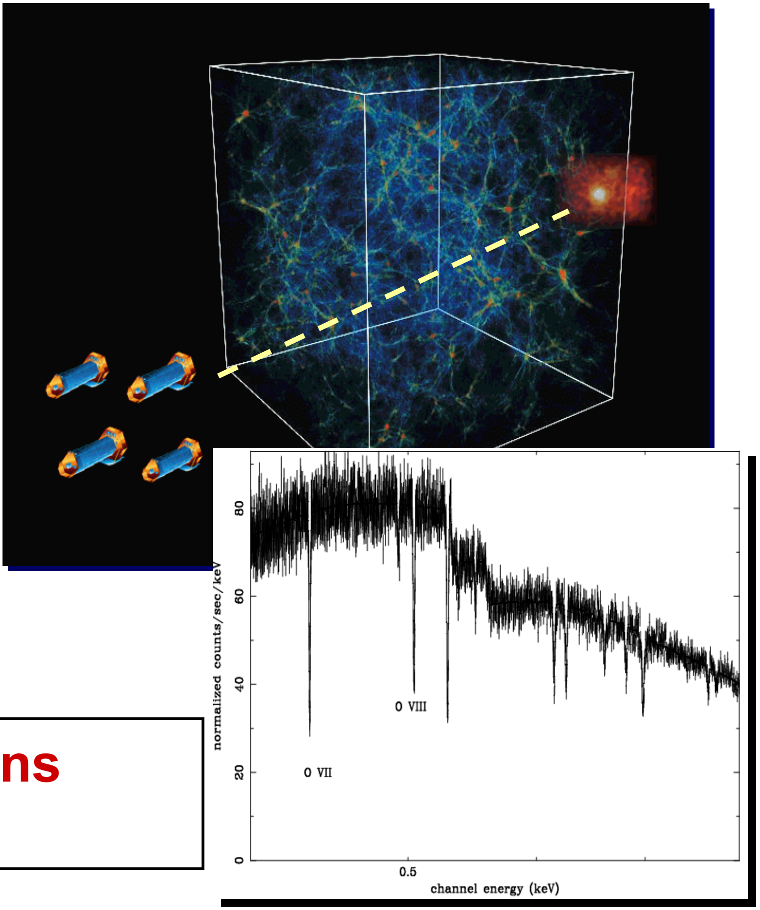
– **Models for the formation of structure under the gravitational pull of dark matter predict the "unseen" baryons are in a 0.1 to 1 million degree K intergalactic gas**

**HST revealed ~15% of these predicted baryons using UV OVI absorption lines seen against bright background Quasars**

**- most sensitive to 0.1 million degree gas**

**Constellation-X will search for the remainder and can detect up to ~70% using O VII and O VIII absorption lines**

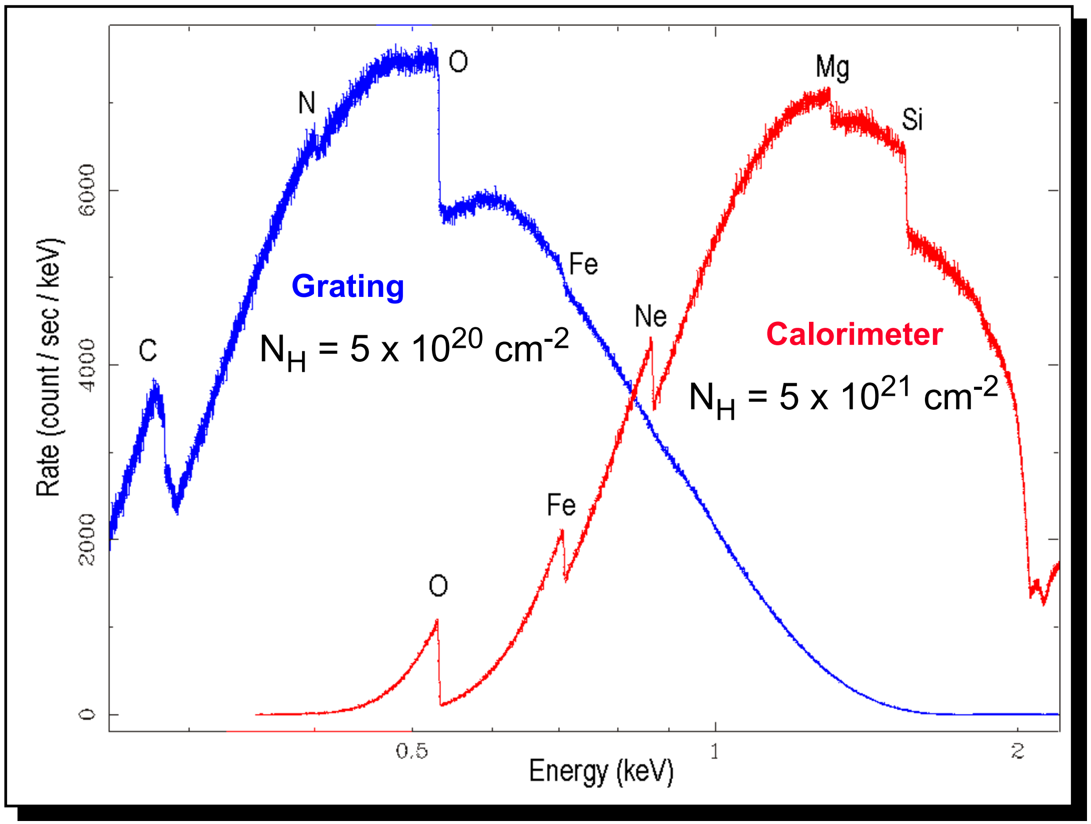
**- most sensitive to 1 million degree gas**



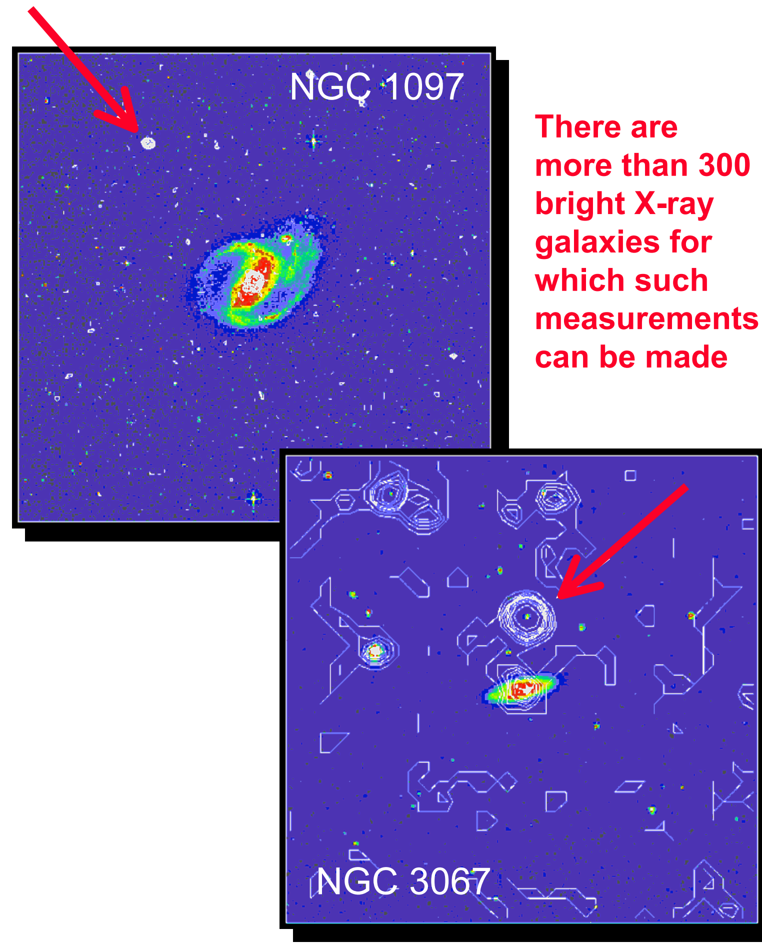

**Together, UV and X-ray observations constrain the problem**

# Galactic Halos

**The composition and state of the tenuous hot halos of Galaxies can be accurately measured via K or L shell absorption of X-rays against background quasars**

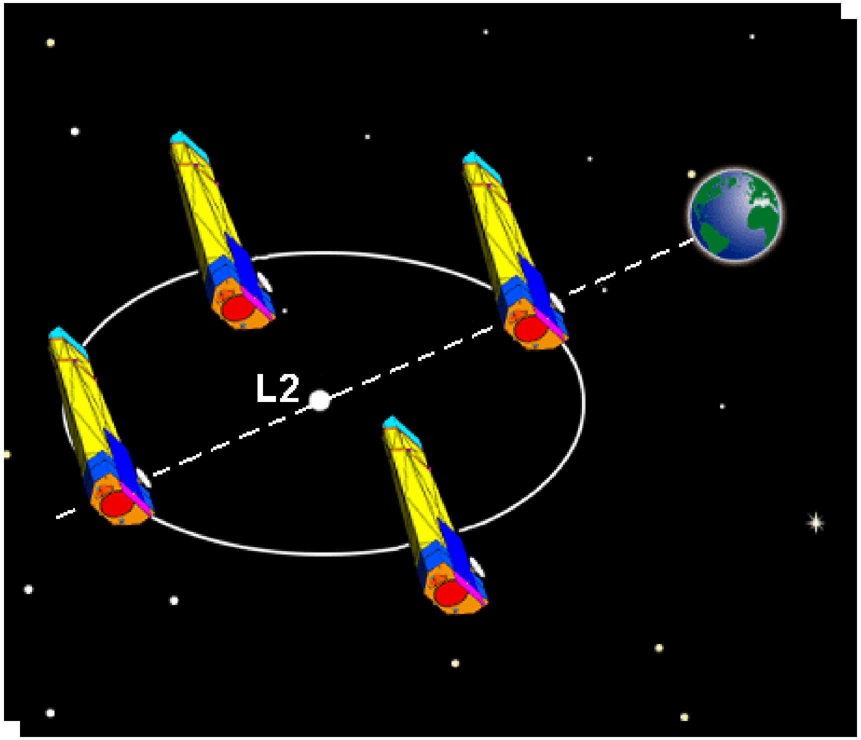



**Spectra of two typical quasars absorbed through two different hydrogen column densities in the ISM**



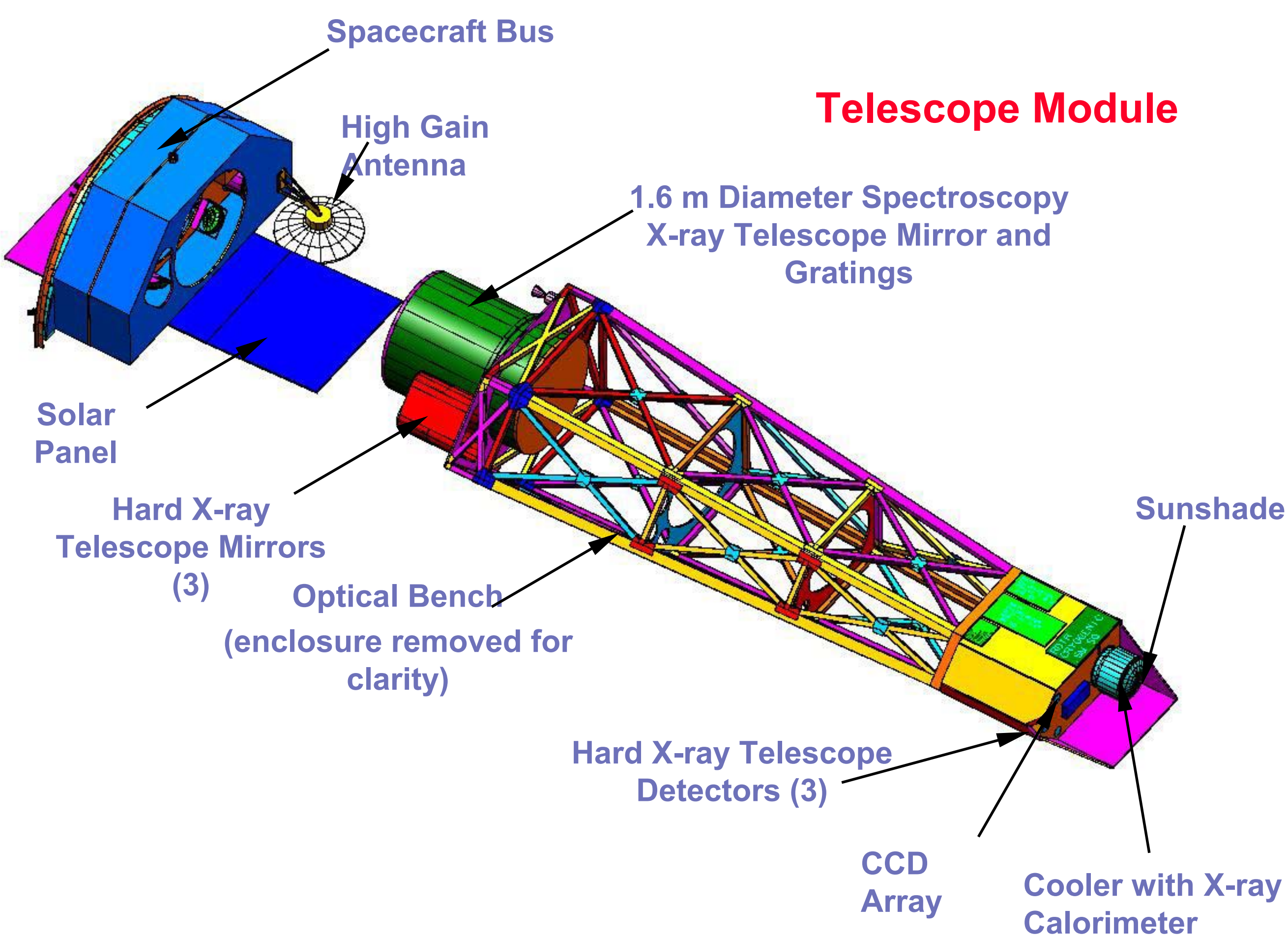

**There are more than 300 bright X-ray galaxies for which such measurements can be made**

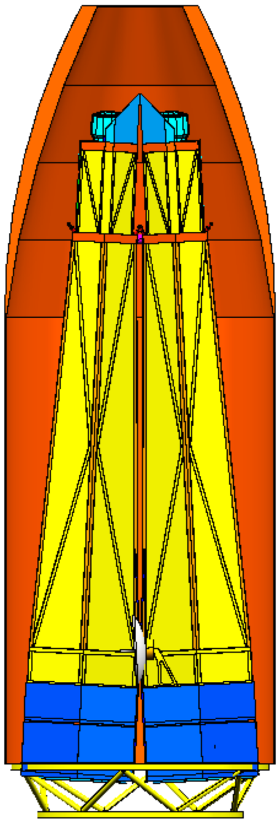
# Constellation-X Mission Concept




- **A multiple satellite approach:**
  - A constellation of multiple identical satellites
  - Each satellite carries a portion of the total effective area
  - Design reduces risk from any unexpected failure
- **Deep space (L2) orbit allows:**
  - High observing efficiency
  - Simultaneous viewing
- **Reference configuration:**
  - Four satellites, launched two at a time on Atlas V class vehicle
  - Fixed optical bench provides a focal length of 10 m
  - Modular design allows:
    - > Parallel development and integration of telescope module and spacecraft bus
    - > Low cost standard bus architecture and components

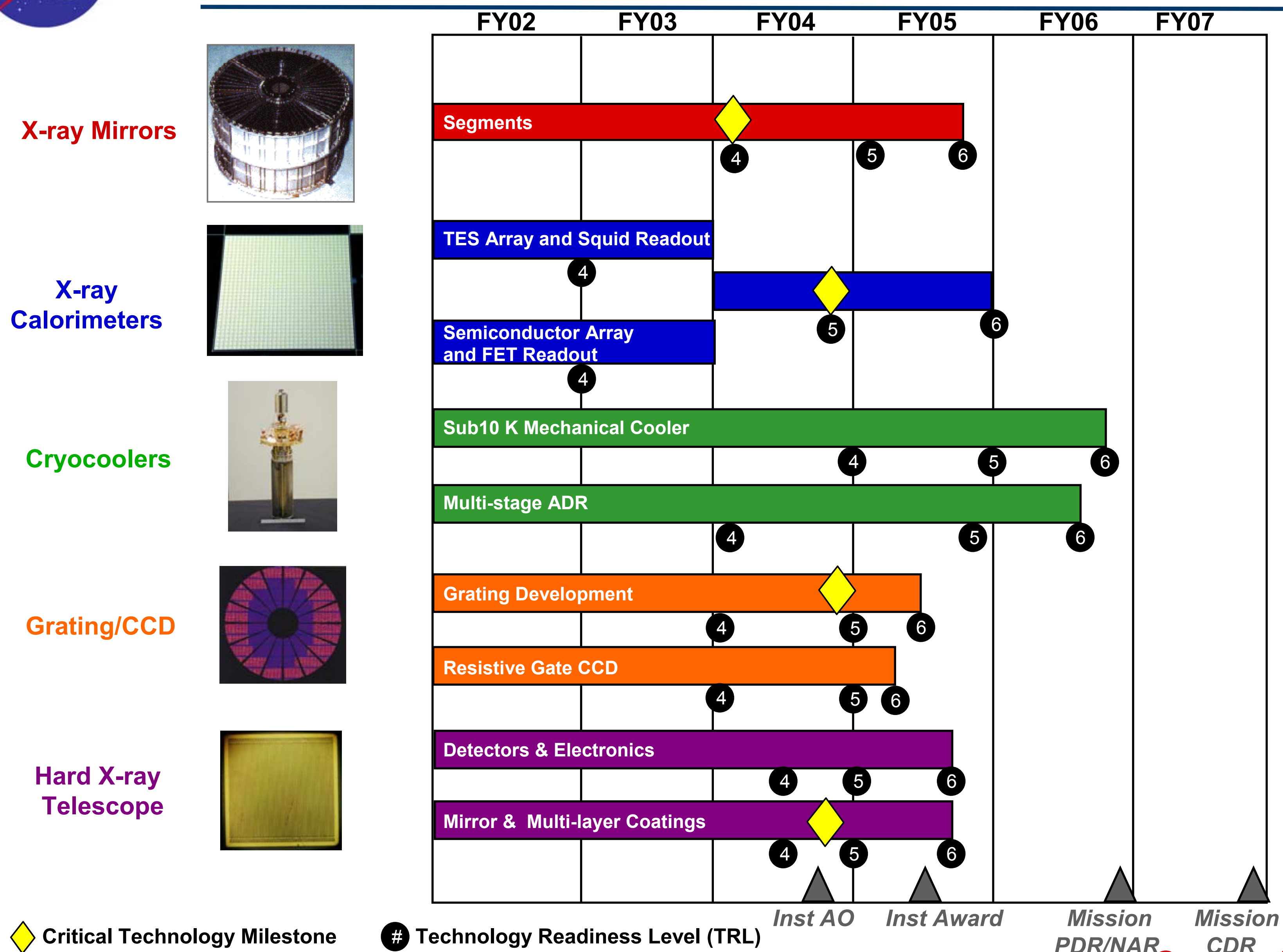
# Reference Design



**Launch Configuration**

# Constellation-X Summary Technology Roadmap



# Highlights from the Past Year

## Mission Accomplishments

- Two meetings of the Facility Science Team
- Planned technology program to meet OMB required technology milestones
- Baselined fixed bench configuration for Reference Configuration
- Identified launch vehicle options
- Continue rigorous requirements flow down documentation

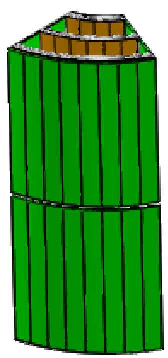
## Technology Progress

- Prioritized segmented optics technology as prime
- Demonstrated mandrel-limited performance on small scale replicated reflectors
- Generated segmented optics modular demonstration approach and began detail design of initial unit
- Initiated procurement of large (1.6 m) segment mandrel
- Achieved flight required energy resolution on single pixel X-ray calorimeters
- Demonstrated ability to make small, close packed TES arrays
- Built first very small X-ray calorimeter TES arrays
- Balloon flight demonstration of hard X-ray imaging using focusing

**Positioned technology to begin flight scale demonstrations**

# SXT Design

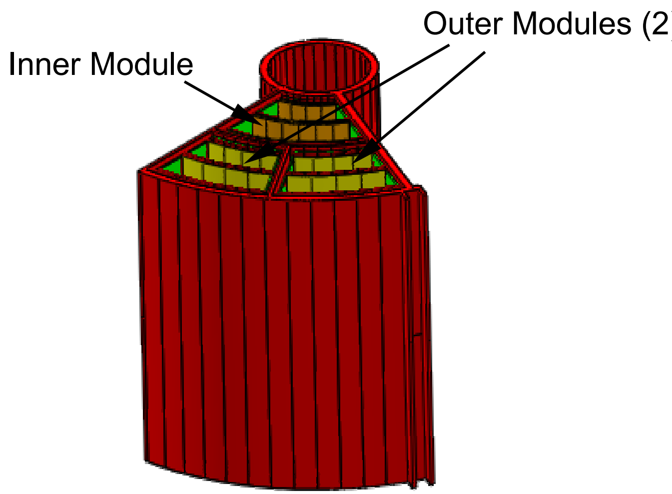
## Engineering Unit



Single inner module with

- 0.5 m dia. reflector pair (replicated from Zeiss precision mandrel)
- Parabolic (P) and Hyperbolic (H) submodules
- First modules to be aligned using etched silicon microcombs

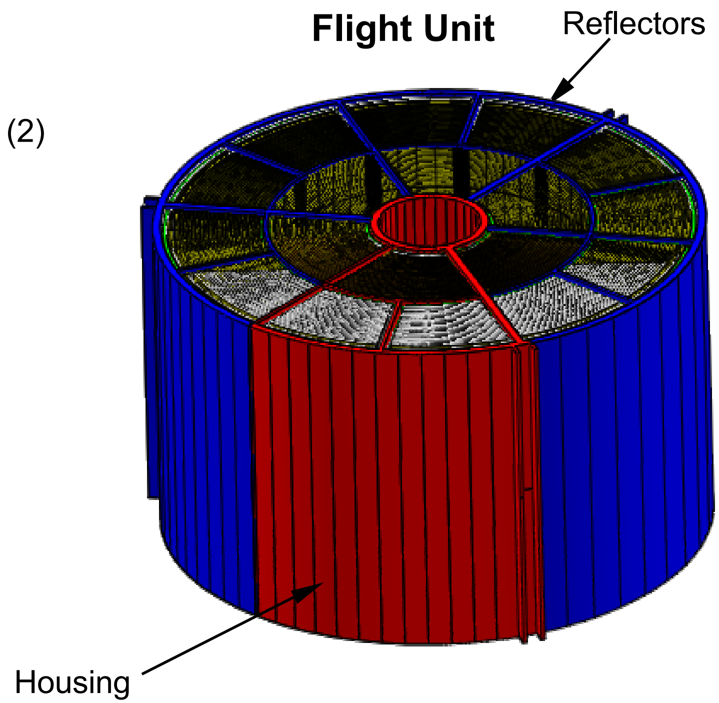
## Prototype Unit




Flight Scale Assembly of

- 3 modules (2 outer and 1 inner)
- Largest diameter same as for flight - 1.6 m
- Each module has 3 to 9 reflector pairs
- Demonstrates module to module alignment

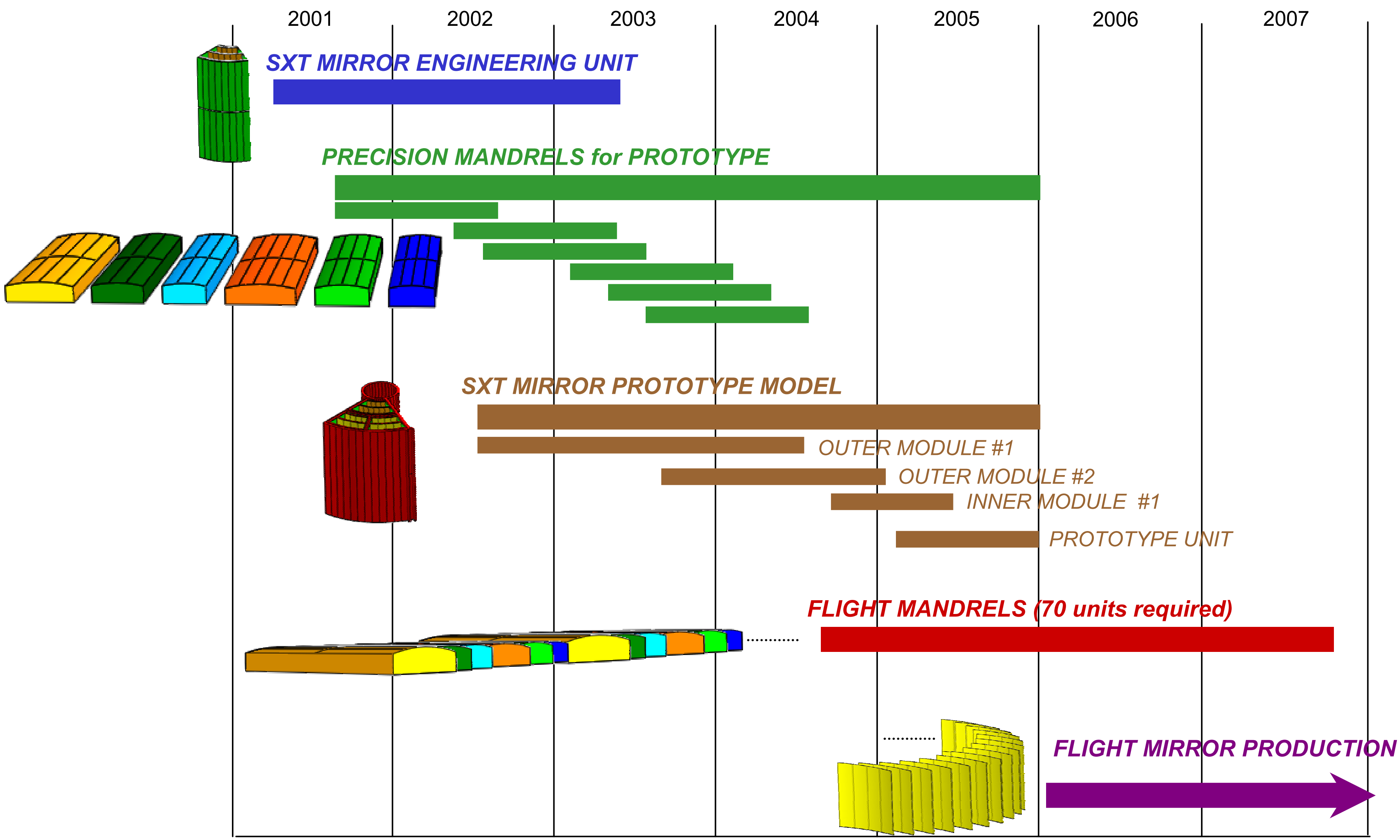
## Flight Unit




Full flight Assembly

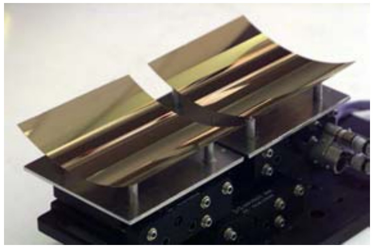
- 1.6 m outer diameter
- 18 Small Modules
- 70 to 170 reflector diameters

# SXT Technology Roadmap

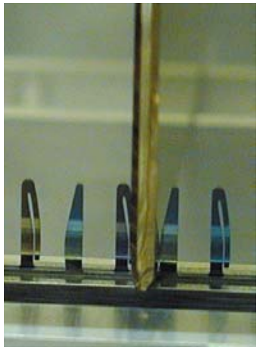


# SXT Segmented X-ray Mirrors

- **Requirement: Highly nested reflectors with 1.6 m outer diameter, low mass and overall angular resolution of 5-15 arc sec (HPD)**
  - Segmented technology meets mass requirement
  - Requires 10 times improvement in resolution and 4 times increase in diameter compared to Astro-E2
  - Now the mission baseline - shell mandrels larger than 0.7m are not available, plus good progress made with demonstrating feasibility of segmented approach
- **Recent Progress:**
  - Demonstrated required performance at component level, necessary to begin system level testing
  - Successfully replicated glass segments from 0.5 m precision Wolter Mandrel with performance limited by forming mandrel
  - Initiated Engineering Unit design
  - Initiated procurement for 1.6 m diameter segment mandrel
- **Partners: GSFC, MIT, SAO, MSFC**



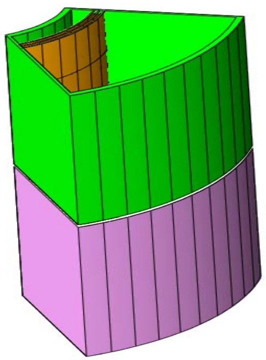
Small glass segment pair on alignment fixture

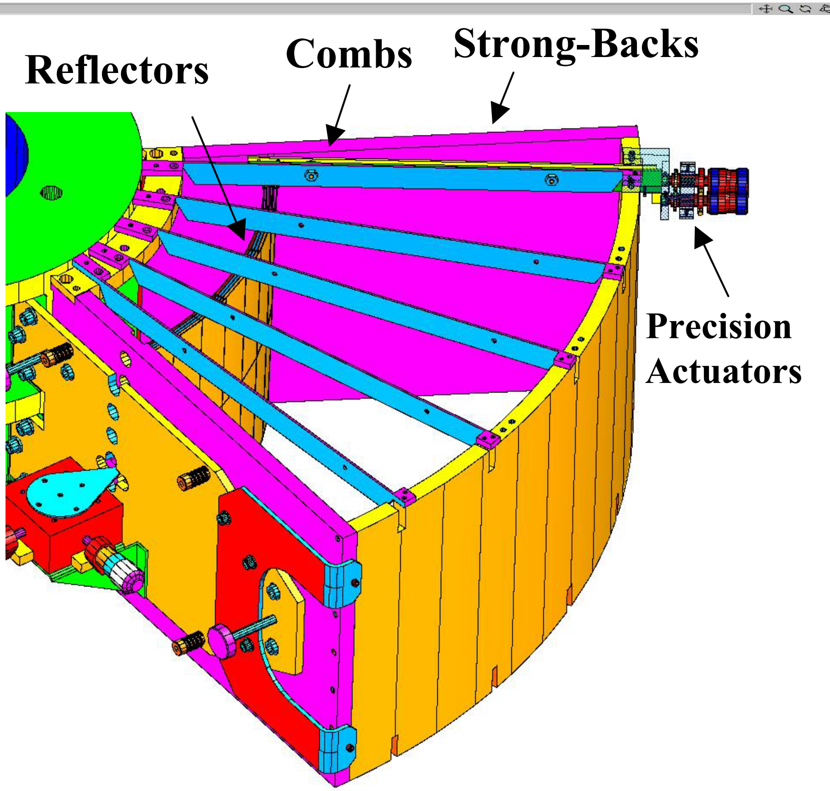


Etched Si alignment microcomb

# SXT Engineering Unit

- **Goal is to approach Con-X resolution requirement in unit incorporating all aspects of SXT flight system**
    - Precisely formed segments
    - Etched Si alignment bars
    - Flight assembly and metrology approach

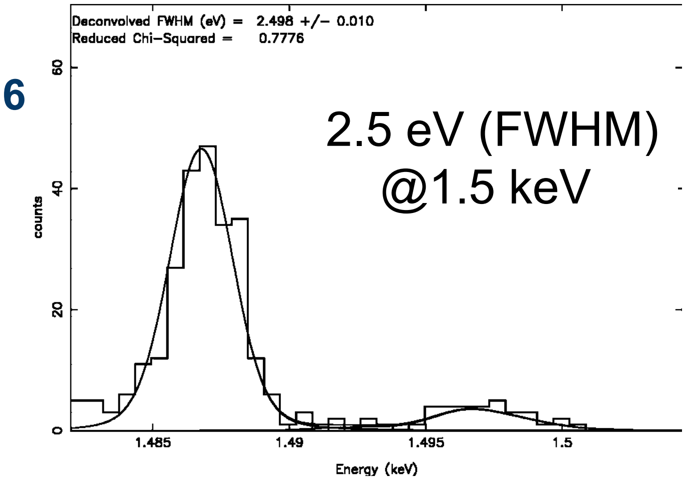


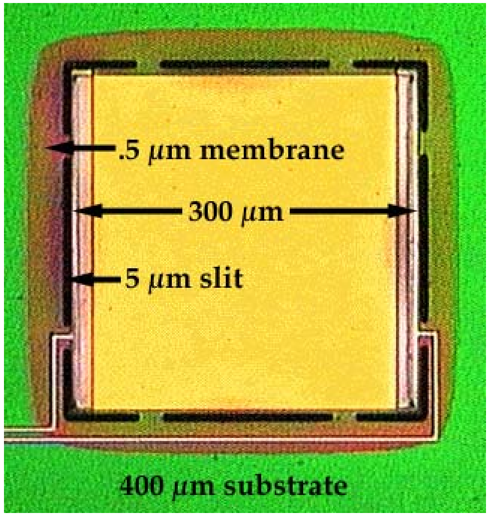



- **EU is flight-like size (inner module)**
- **Utilizes existing Zeiss metal mandrels**
  (50 cm dia.; 8.4 m f.l.; 5” surface)
- **Phased build up, with increasing complexity**
- **Units will be tested in X-rays and subjected to environmental testing**
- **Delivery mid-2003**

# X-ray Calorimeters

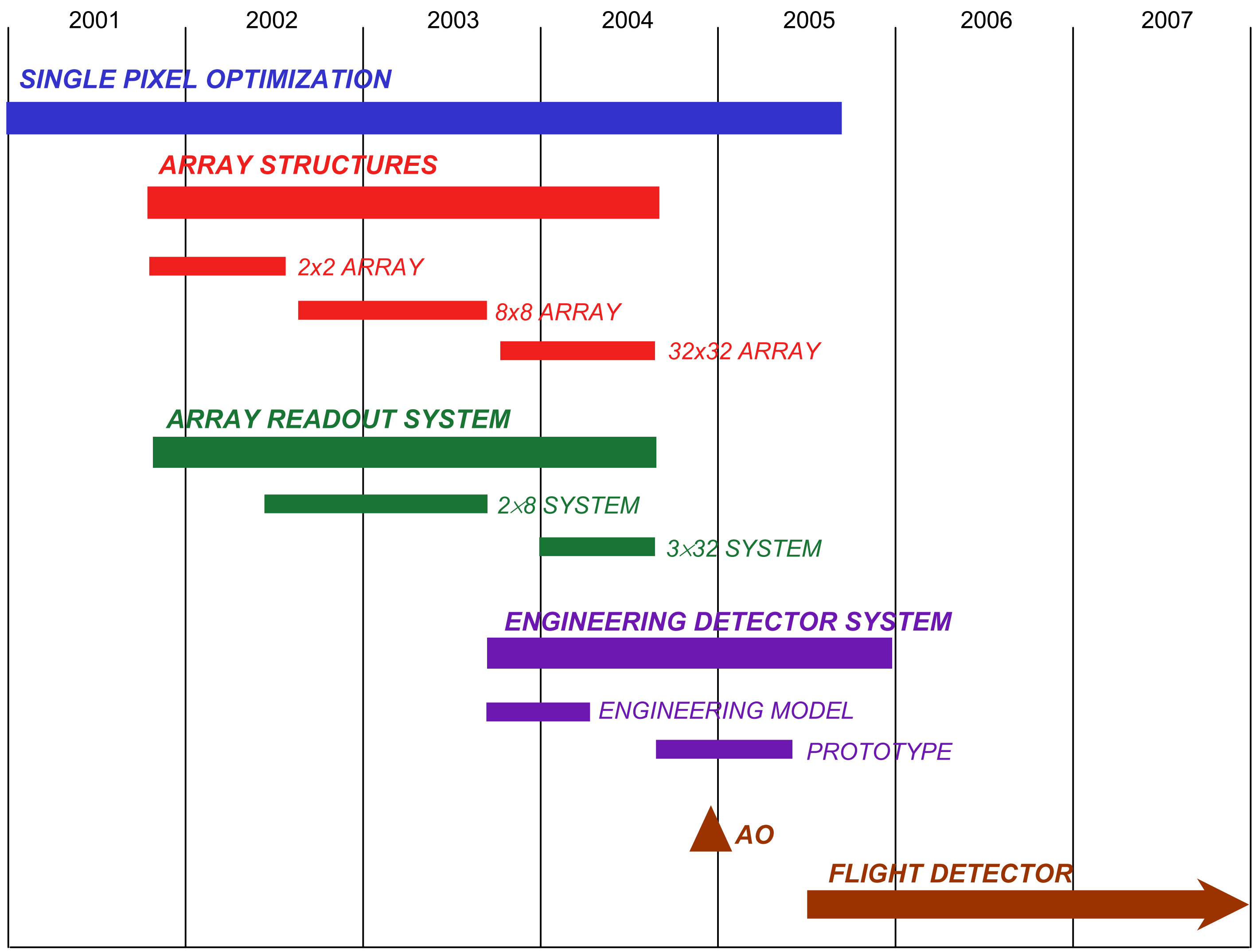
- Requirement: 2 eV FWHM energy resolution from 1 to 6 keV at 1000 counts/s/pixel in 32 x 32 pixel array
- Parallel Approach: Transition Edge Sensor (TES) and NTD/Ge Calorimeters
- Progress:
  - Demonstrated 2 eV resolution at 1.5 keV and 4 eV at 6 keV using TES approach on demonstration devices
  - Achieved adequate thermal isolation and 2.5 eV resolution at 1.5 keV using a flight sized TES device
  - Quantified TES detector noise to enable energy resolution budget
  - Fabricated 2 $\times$ 2 TES array for initial cross talk measurements
  - Demonstrated a new imaging TES approach that will potentially enable increase in field of view
  - Achieved 4.8 eV resolution over full range (1-6 keV) with NTD/GE detector




- Partners: GSFC, NIST, SAO, UW, LLNL, Stanford

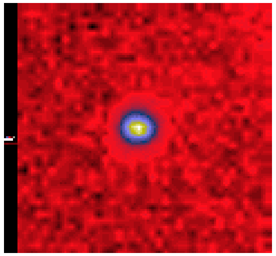
# X-ray Calorimeter Technology Roadmap



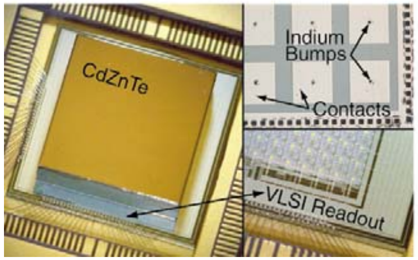
# Constellation-X Hard X-ray Telescope

- **Requirement: Maximum energy $\geq$ 40 keV, effective area $\geq$ 1500 cm$^2$, angular resolution $\leq$ 1 arc min HPD, FOV 8 arc min, energy resolution $\leq$ 10%**
- **Approach: Depth-graded multilayer grazing incidence optics (shell or segmented) and CdZnTe pixel detectors**
- **Progress:**
  - **Successful balloon flights (HERO and Infocus) in 2001 demonstrated first focused hard X-ray images**
  - **Improved CdZnTe detector performance**
    - **Energy resolution 390 eV (at 18 keV) and 550 eV (at 60 keV)**
    - **Threshold (theoretical) is 2 keV – 8 keV demonstrated**
  - **Demonstrated sputter coating on interior of cylindrical shells**
  - **Evaluated formed glass prototype optic with 5 coated surfaces**

    **< 60 arc sec HPD and good reflectance at 60 keV (single bounce)**

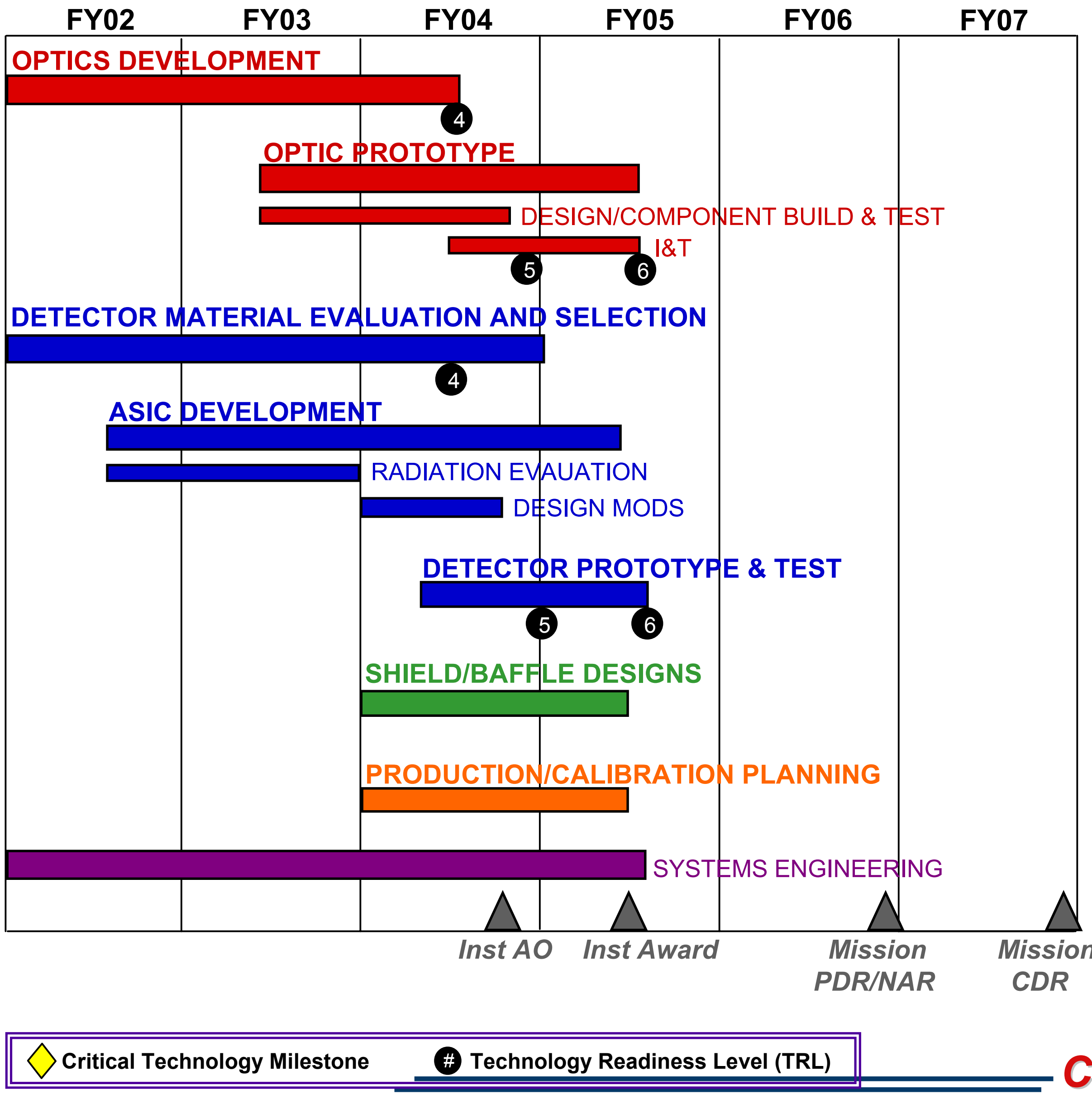


68 keV image glass prototype




– **Partners: Caltech, GSFC, Columbia U., MSFC, Harvard, SAO, NU, NRL**

# HXT Technology Roadmap



# Critical Technology Development Milestones

| Milestone | Date |
|---|---|
| Spectroscopy X-ray Telescope (SXT) Optic Engineering Unit | 1Q FY04 |
| Small X-ray Calorimeter Array | 3Q FY04 |
| Flight Representative Lightweight Grating Substrates | 4Q FY04 |
| Hard X-ray Telescope (HXT) Optics Demonstration Unit | 4Q FY04 |

# Critical Technology Milestones

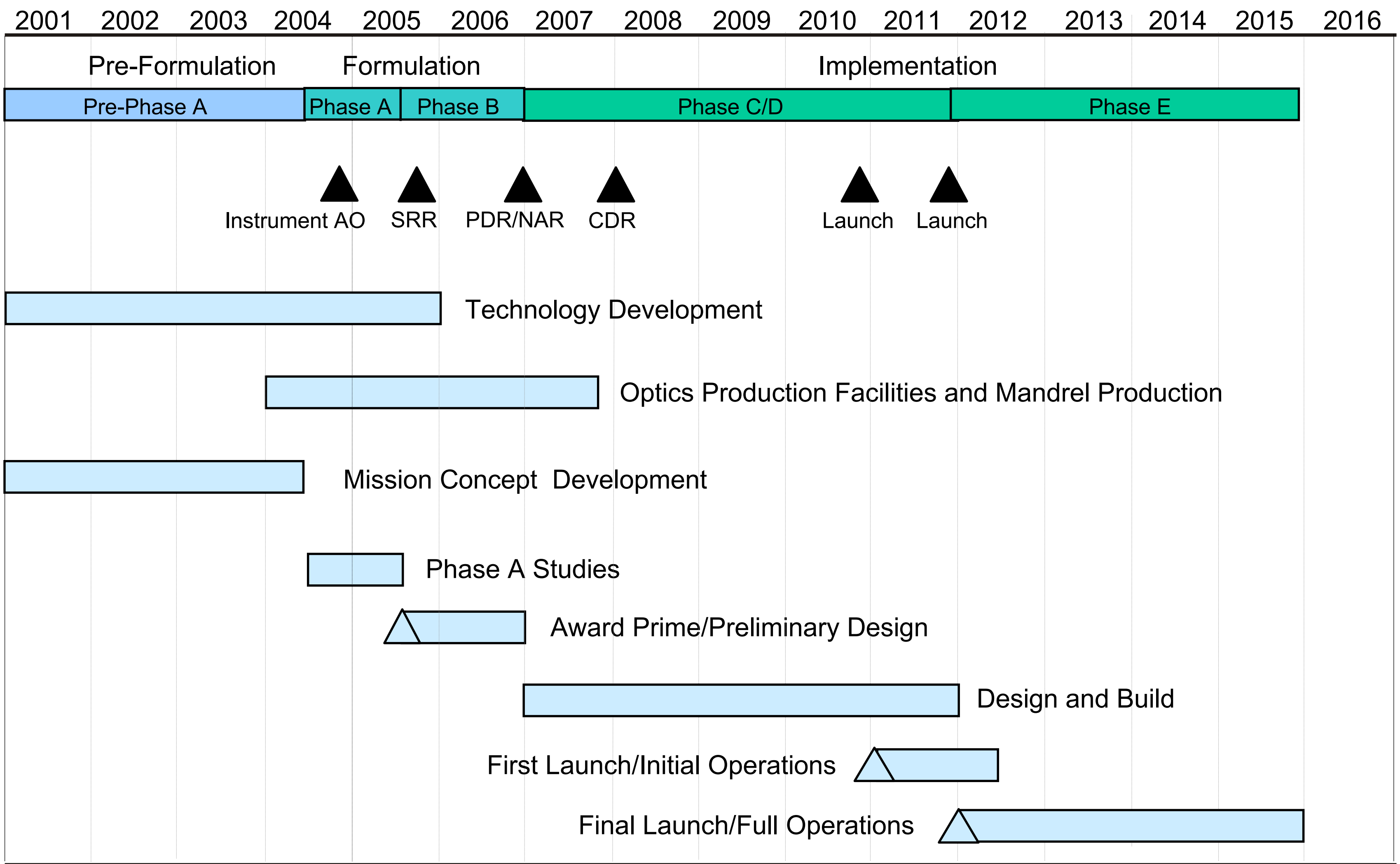
- **SXT Optic Engineering Unit Completed and Tested in X-rays**
  - Alignment comb fabrication process verified.
  - Assembly and alignment procedures established.
  - Optical performance understood and extendable to 10 arc sec.
  - Replication process satisfies requirements and is reproducible.
  - Reflector support concept verified.
  - Preliminary mechanical testing satisfactorily completed.

- **Small X-ray Calorimeter Array Fabricated and Tested**
  - Pixel scale and quantum efficiency appropriate to Constellation-X baseline requirements.
  - Energy resolution of 2 eV at 1.5 keV and 4 eV or better at 6 keV, simultaneously in each pixel.

# Critical Technology Milestones Cont'd

- **Assembly of Three Flight Representative Lightweight Grating Substrates**
  - Substrates fabricated use procedures that can be applied to mass production and experience all processing steps that are included in the plan for the final flight gratings.
  - Substrate mass per unit area $\leq$ 0.2 gm/cm^2.
  - Substrate as-assembled flatness $\leq$ 2 arc-seconds in the dispersion direction.
  - Substrate mutual alignment $\leq$ 2 arc-seconds in the dispersion direction.
- **Hard X-ray Multilayer Mirror Protytype Completed and X-ray Tested**
  - Angular resolution $\leq$ 1 arc minute (Half Power) Diameter at 20 keV.
  - Mass and reflectance consistent with the baseline mission requirements.
  - Multilayer mirror fabrication process verified.

# Top Level Schedule
## (In-guide FY07 New Start)



# Constellation-X Top Level Schedule

Schedule designed to establish continuity and overlap with Chandra & XMM-Newton

Activities and future plans:

- Mission in formulation since 1997
- Technology program well underway, with critical milestones in 2004
- Instrument AO in fall of 2004
- Mission implementation (C/D) start 2007
- First Launch 2010, with second launch one year later

# Summary

- **Constellation-X emphasizes high throughput, high spectral resolution observations – the next major objective in X-ray astronomy**
  - A High Priority Facility in the influential McKee-Taylor Decadal Survey

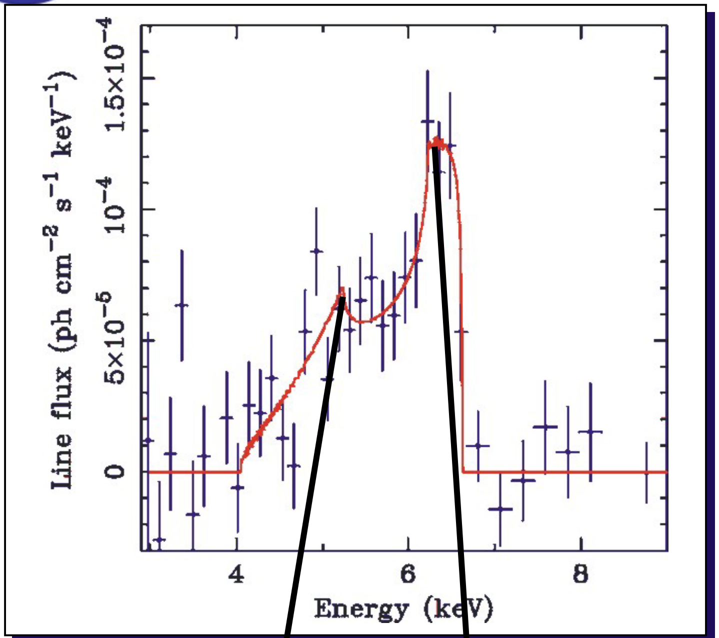
- **Mission design is robust and low risk**
  - Assembly line production and multi-satellite concept reduces risk
  - First launch in 2010 timeframe
  - Facilitates ongoing science-driven, technology-enabled extensions

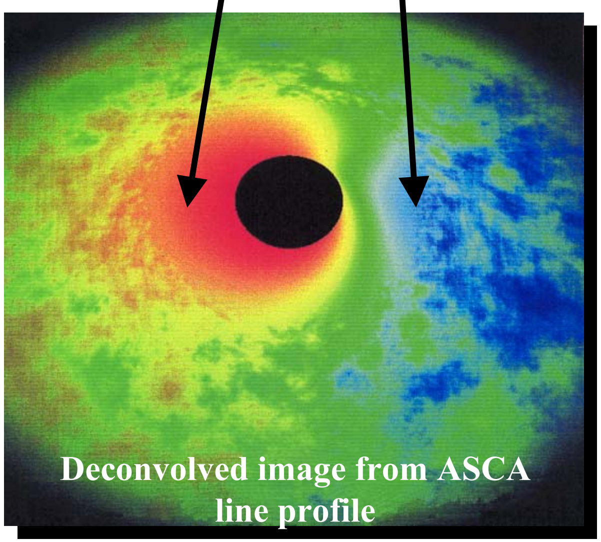
- **Substantial technical progress achieved**
  - Replicated segmented reflector performance at component level
  - Calorimeter single pixel spectral resolution
  - Hard X-ray telescope optics and detector performance

- **Ramping up flight scale technology development program**
  - On track to demonstrate critical milestones by FY04

# Back up charts

# Relativistic Iron Lines



Deconvolved image from ASCA line profile

- ASCA discovered a relativistically broadened iron line that come from close to the event horizon of black holes in the nucleus of nearby galaxies
- This line provides a unique probe of the inner sanctum near black holes, observing the effects of GR in the strong gravity limit
- Much larger collecting area and improved energy resolution required to exploit this diagnostic
  - Constellation-X is designed for this

# Constellation-X and HST Constraints on the Hot Intergalactic Medium

**Hubble Limit:**

~15% of baryons detected using OVI absorption lines assuming ionization fraction of 0.2 and oxygen metallicity of 0.5

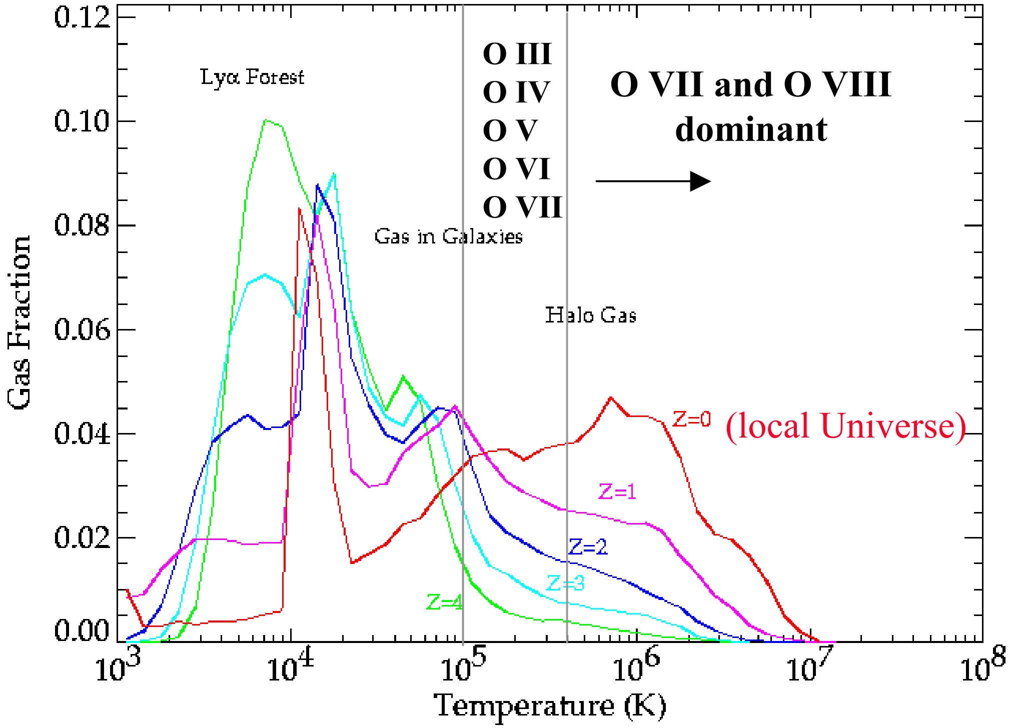
~ O VI line alone does not uniquely constrain the temperature or ionization fraction

**Constellation-X Limit:**

No assumption of ionization fraction needed!

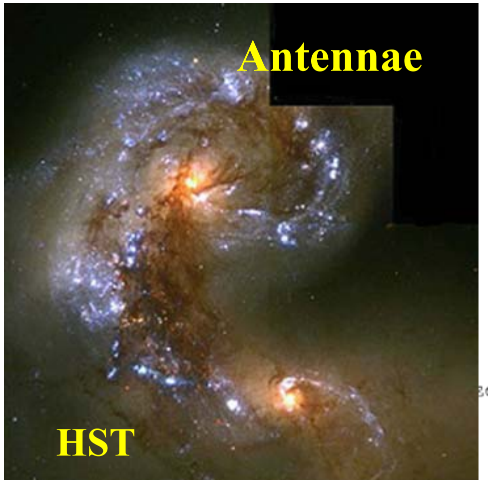
~70% of baryons detected using O VII and O VIII resonant absorption lines

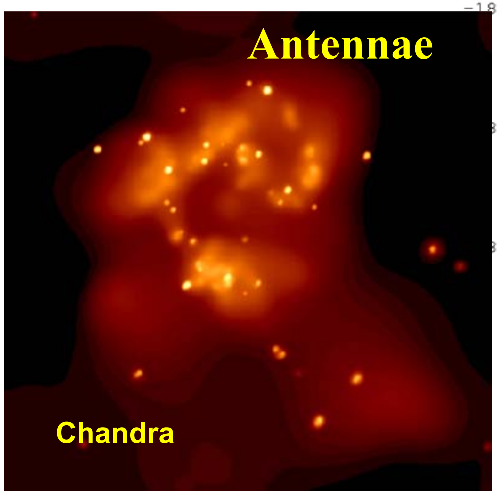
**Distribution of gas temperature at different Cosmic epochs**



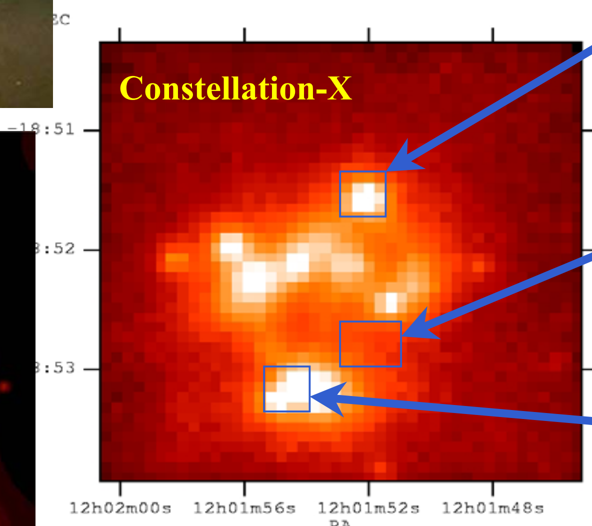

**Together UV and X-ray constrain the problem**

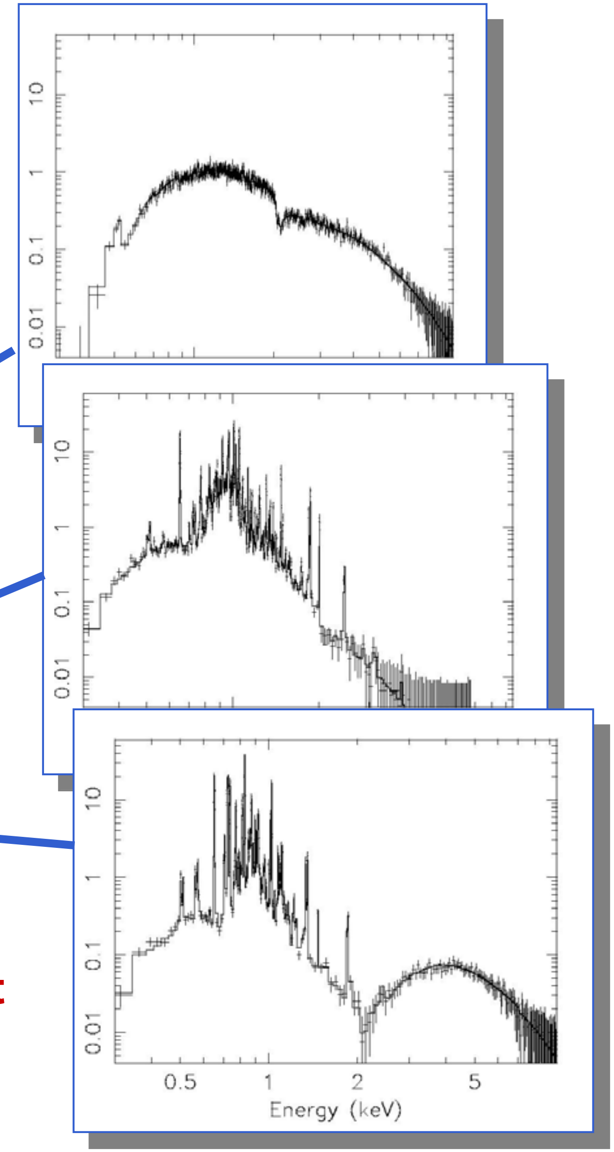
# Hot ISM in Spiral Galaxies: The Antennae



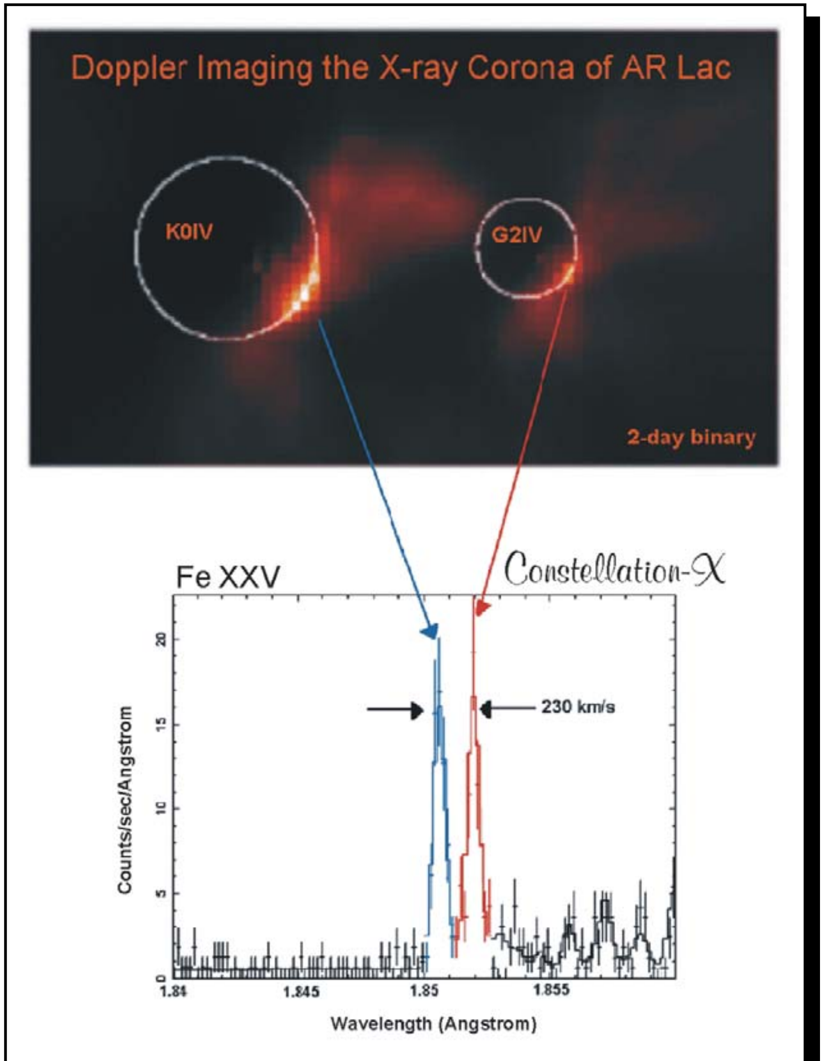

**Constellation-X needed to map the hot IGM in the Antennae to determine the plasma parameters (density, abundance, velocities, ionization state) of the hot ISM**



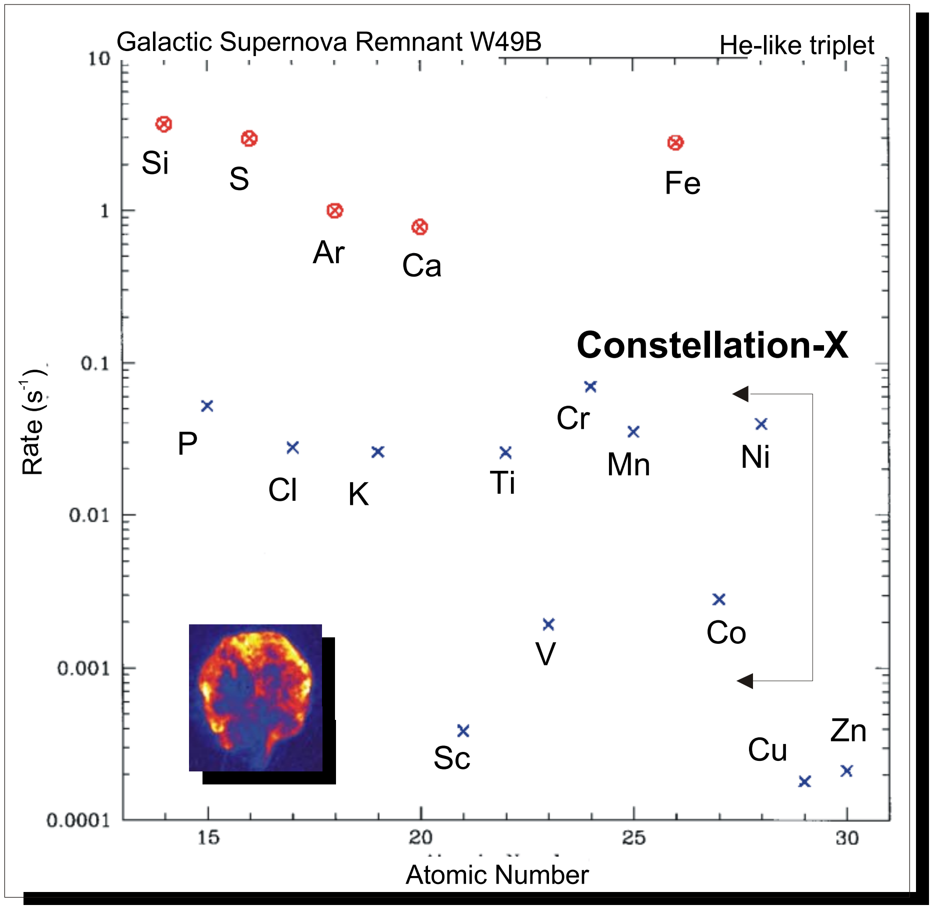

**Constellation-X will complement Chandra by giving 900 high resolution spectra across the galaxy in one observation**

# Constellation-X Observations of Stellar Coronae




- Plasma spectroscopy and Doppler imaging of coronal activity in stars
- Study magnetic reconnection, mass motion, densities, and abundances in stellar flares
- Investigate the formation and evolution of magnetic dynamos in young and pre-main sequence stars in molecular clouds
- Obtain high resolution spectra of stellar coronae from a wide range of luminosity
- Obtain high quality spectra of active stars such as RS CVn and Algol systems out to ~30 kpc

# Constellation-X Measurements of Chemical Enrichment in SNRs




**Determine the abundance and velocity distribution of even- and odd-Z elements from Carbon to Zinc in extended supernova remnants**

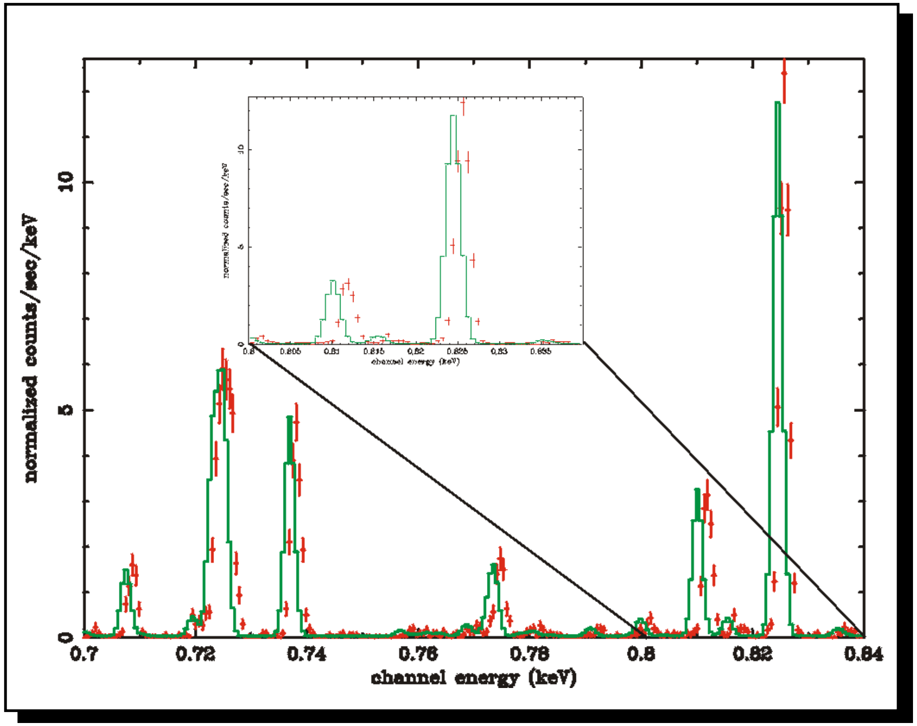
**Significant detection of odd-Z elements achieved by Constellation-X in less than 20 ks will investigate the processes that lead to their production (beyond the $\alpha$-processes)**

**Search for non-thermal components using the HXT to constrain Cosmic Ray models**

Credit: Jack Hughes

# Dark Matter Distribution in Spiral Galaxies

- Rotation curves of cold gas and stars prove existence of dark matter halos. Since stars and gas are confined to the plane of the galaxy, the rotation curves probe only <u>2D distribution</u> of dark matter
- By measuring the T and r distribution of hot gas surrounding the galaxy, as well as its rotational velocity, the <u>3D distribution</u> of dark and luminous matter in the galaxy can be determined
- Expected rotation velocities are ~ 300 km $s^{-1}$ - well within Constellation-X capabilities




**A 50 ks simulated observation of the hot halo gas in the edge-on spiral galaxy NGC 891. The solid line shows 0.3 keV gas model shifted by 600 km/s (assuming halo circular velocity of 300 km/s based on disk measurements).**

***Credit: Diana Worrall***

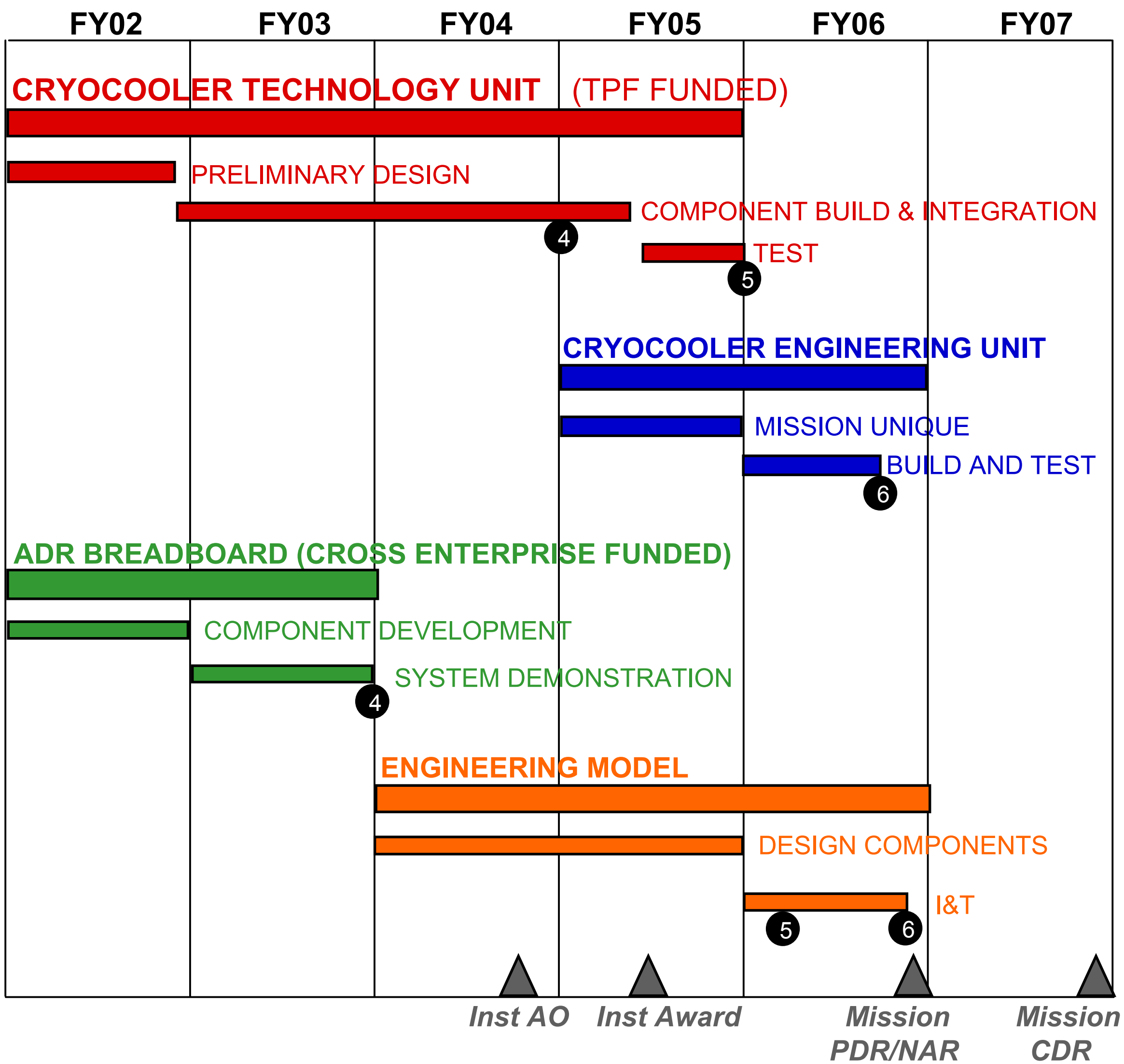
# Cooling System for X-ray Calorimeter

- **Requirement: Long life cooling system to provide 40 to 65 milli Kelvin to X-ray calorimeter**
- **Approach: Sub10-Kelvin mechanical cooler to provide heat sink to sub-Kelvin Adiabatic Demagnetization Refrigerator (ADR)**
- **ADR Progress:**
  - Demonstrated operation of two new heat switches: a gas-gap switch and a magneto resistive switch
  - Assembling a three-stage continuous ADR demonstrator using these heat switches and previously developed components over the next few months
  - Identified engineered refrigerants that may offer lower magnetic fields and higher cooling power in the 1-10 K range
  - Funded by Cross Enterprise Technology Development Program
- **Mechanical Cooler Progress:**
  - 70 K turbo-Brayton cooler for HST successfully completed mechanical and thermal testing
  - Performed highly successful 6-10 K flow-through test of the Turbo alternator
  - Funded by Cross Enterprise Technology Development Program and SBIR

**Turbo-alternator Test Apparatus**

- **Partnership: GSFC, JPL, Creare, Energen, Houston U., Berkley**

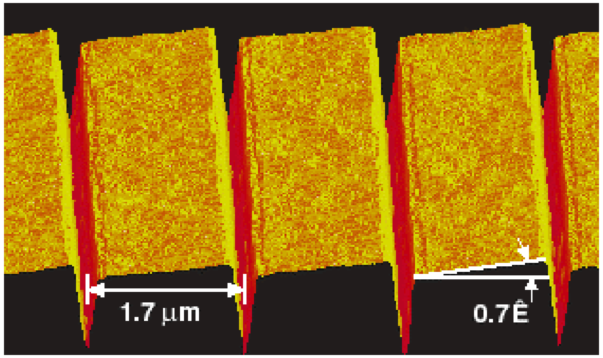
# Cryocooler and ADR Technology Roadmap




Critical Technology Milestone   # Technology Readiness Level (TRL)

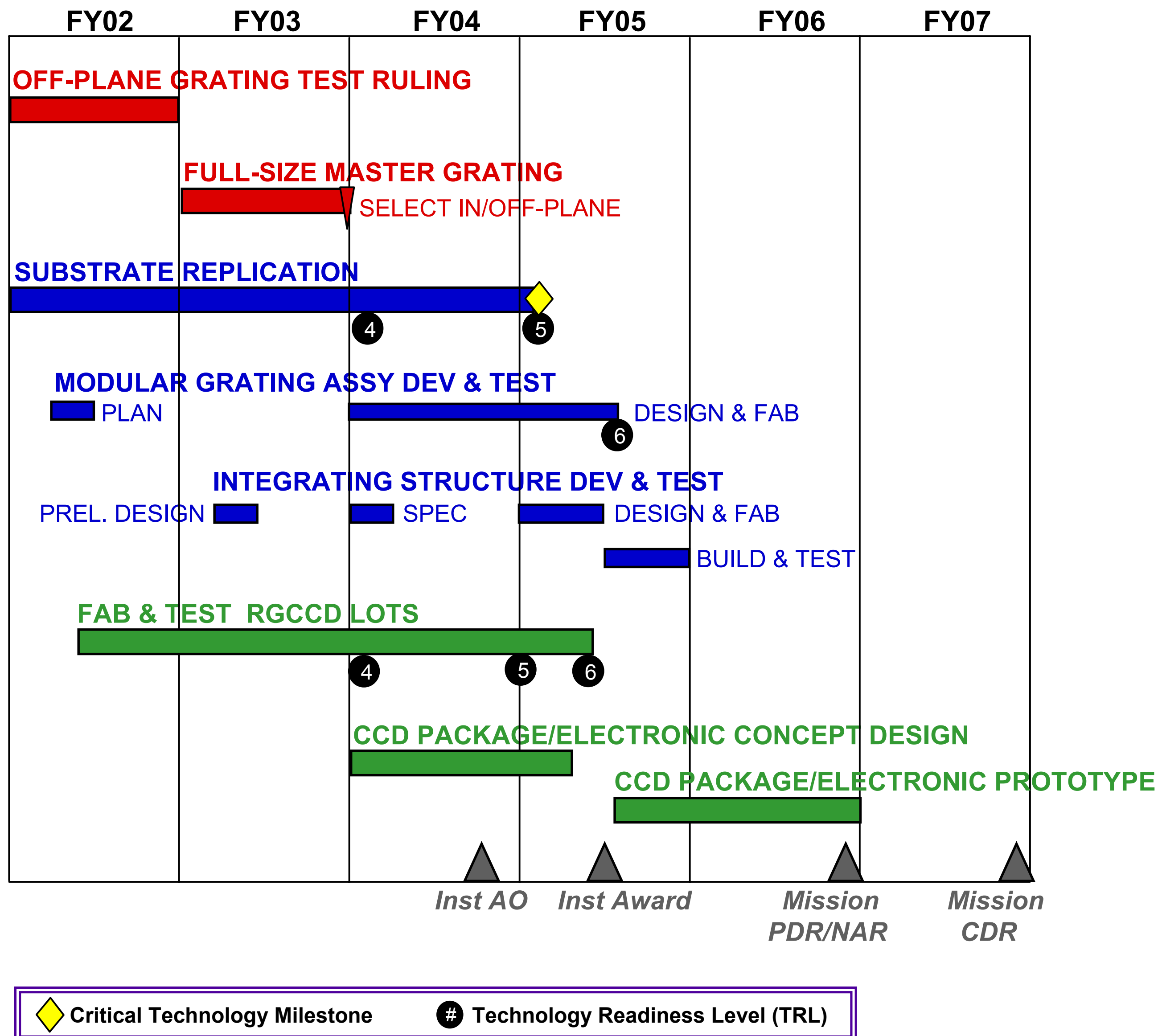
# Constellation-X Reflection Gratings / CCD

- **Requirement: High throughput, high resolution reflection grating spectrometer for 0.25 keV to 2.0 keV, with low mass and producible from high yield processes**
- **Approach: In-plane and off-plane approaches being investigated. Anisotropic Interference lithography on silicon wafers; and resistive gate CCDs**
- **Partners: Columbia U., Colorado U., MIT, Penn State U.**
- **Progress:**
  - **Measured efficiency ~23% for prototype grating at 1.5 keV**
  - **Demonstrated process for reducing large-scale warping of grating substrate**
  - **First lot of Resistive Gate CCDs demonstrate concept**
- **Plans:**
  - **Demonstrate technique for achieving small scale flatness (0.1 micron) over entire grating substrate**
  - **Develop fabrication plan for second lot RGCCD; address resistance uniformity for charge transfer**



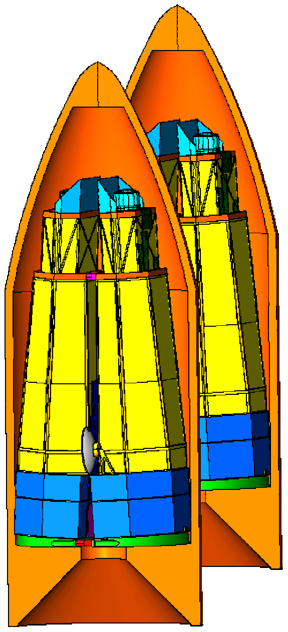

Fabricated with anisotropic etches on silicon

# Grating/CCD Technology Roadmap

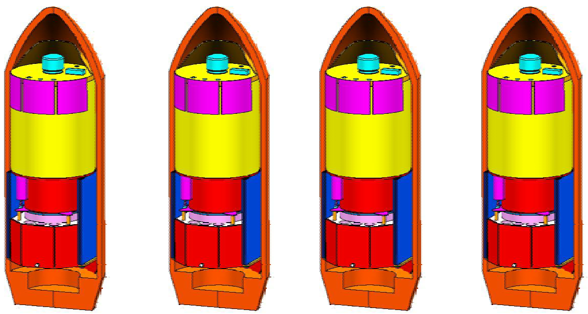


# Launch Vehicle Options

- **Atlas V is optimal for Constellation-X (2 launches)**
  - Most effective means to meet full mission performance
  - Thirteen launches currently planned prior to Constellation-X new start in October 2006
- **Delta IV Medium could be used (2 launches)**
  - Requires single deployable extension on optical bench to obtain full 10 m focal length
  - Seventeen launches planned prior to October 2006
- **Delta II could be used (4 launches)**
  - Approximately 12 percent reduction of total mission effective area
  - Requires extendible optical bench
  - Uses solar electric power ion propulsion
  - Takes 450 days to reach L2

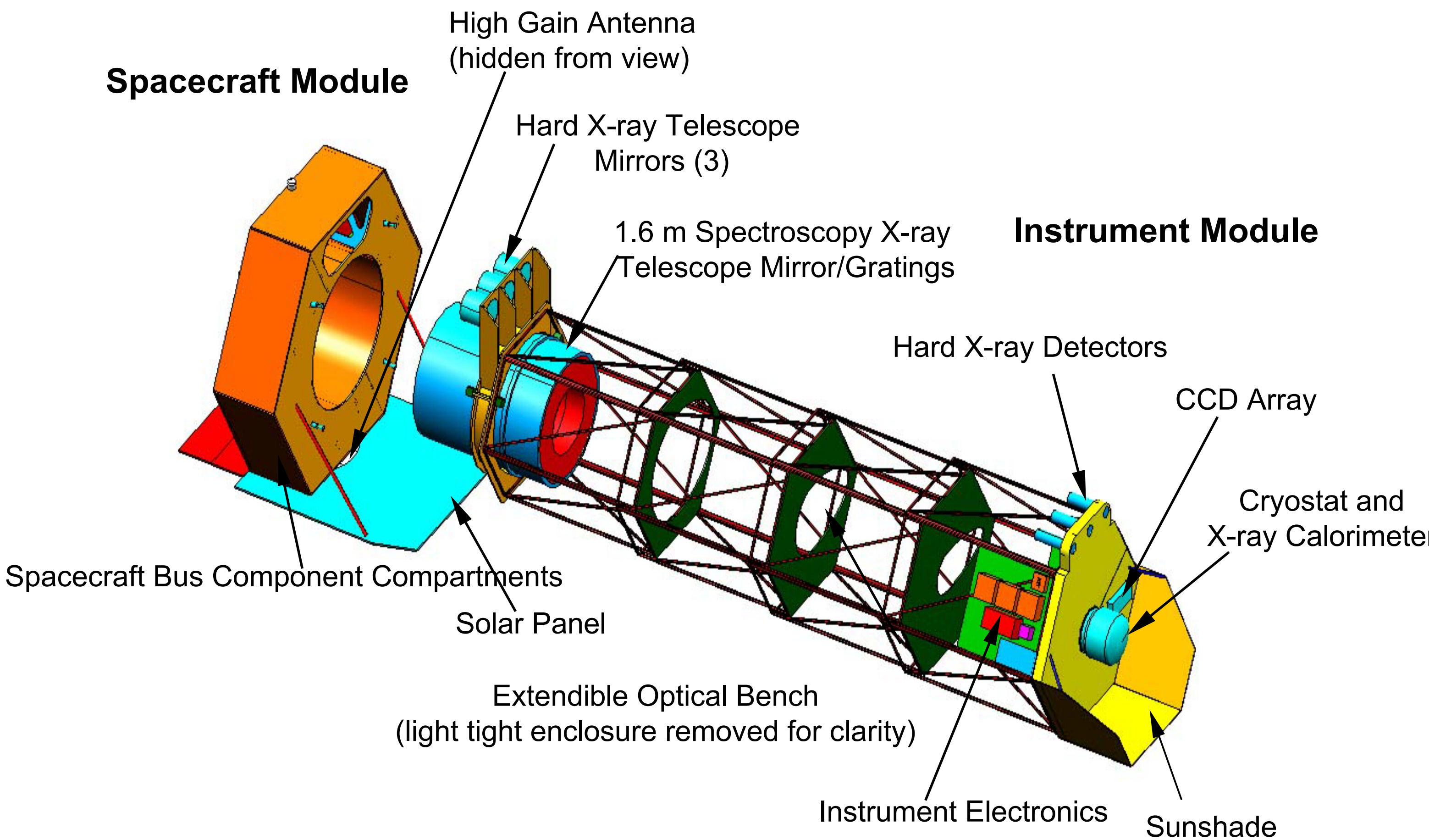


Delta IV



Delta II

# Constellation-X Extendible Design



# Constellation-X Requirements Flow Down

## Science Goals

**Parameters of Supermassive Black Holes**

**Search for Dark Matter**

**Investigate Faint Sources**

**Plasma Diagnostics from Stars to Clusters**

## Measurement Capabilities

**Effective area:**
15,000 cm² at 1 keV
6,000 cm² at 6.4 keV
1,500 cm² at 40 keV

**Band pass:**
0.25 to 40 keV

**Spectral resolving power ($E/\Delta E$):**
$\geq$ 300 from 0.25 to 6.0 keV
$\geq$ 3000 at 6 keV
$\geq$ 10 at 40 keV

**System angular resolution and FOV:**
15 arc sec HPD and
FOV > 2.5' (0.25 to 10 keV)

1 arc min HPD and
FOV > 8' (10 to 40 keV)

## Engineering Implications

**Effective area:**
- Light weight, highly nested, large diameter (1.6 m) optics
- Long focal length (8-10 m)

**Band pass:**
- 2 types of telescopes to cover energy range

**Spectral resolving power:**
- Dispersive *and* non-dispersive capability to cover energy band

**System angular resolution and FOV:**
- Tight tolerances on telescope figure, surface finish, alignment
- $\geq$ 30 x 30 array for x-ray calorimeter (pixels ~5")
- Cryocooler driven by array size and readout electronics

## Key Technologies

**High throughput optics:**
- High performance replicated segments and shells
- High reflectance coatings
- High strength/mass materials for optical surfaces

**High energy band:**
- Multilayer optics
- CdZnTe detectors

**High spectral resolution:**
- 2 eV calorimeter arrays
- Coolers
- Lightweight gratings
- CCD arrays extending to 0.25 keV

**Optical bench:**
- Stable (time and temp.)
- High strength/low weight materials